

# Handbook of Industrial Water Soluble Polymers

Edited by

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**Blackwell**  
Publishing

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Blackwell Publishing editorial offices:

Blackwell Publishing Ltd, 9600 Garsington Road, Oxford OX4 2DQ, UK

Tel: +44 (0)1865 776868

Blackwell Publishing Professional, 2121 State Avenue, Ames, Iowa 50014-8300, USA

Tel: +1 515 292 0140

Blackwell Publishing Asia Pty Ltd, 550 Swanston Street, Carlton, Victoria 3053, Australia

Tel: +61 (0)3 8359 1011

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First published 2007 by Blackwell Publishing Ltd

ISBN: 978-1-4051-3242-8

Library of Congress Cataloging-in-Publication Data

Handbook of industrial water soluble polymers / edited by Peter A. Williams

p. cm.

Includes bibliographical references and index.

ISBN: 978-1-4051-3242-8 (hardback : alk. paper)

1. Water-soluble polymers. I. Williams, Peter A.

QD382.W3H35 2007

668.9—dc22

2006035213

A catalogue record for this title is available from the British Library

Cover image is adapted from Steward, P.A., Hearn, J. & Wilkinson, M.C. (1995) Studies in permeation through polymer latex films. II. Permeation modification by sucrose addition. *Polymer International* **38** (1), 13–22. Copyright Society of Chemical Industry. Reproduced with permission. Permission is granted by John Wiley & Sons Ltd on behalf of the SCI.

Set in 10/12 pts Minion

by Charon Tec Ltd (A Macmillan Company), Chennai, India

[www.charontec.com](http://www.charontec.com)

Printed and bound in Singapore

by COS Printers Pte Ltd

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## Chapter 1

# Introduction

*Peter A. Williams*

Water soluble polymers are widely used in a broad range of industrial products and processes including, foods, pharmaceuticals, cosmetics, personal care products, paints and other coatings, inks, pigments, construction materials, adhesives, paper making, paper coating, water clarification, effluent treatment, etc. The polymers may be natural or synthetic with an array of molecular chemistries, structures and sizes. Although often present at very low concentrations they have a very significant influence on the overall properties of products and on product processing.

They have a number of key functionalities, including their ability to:

- increase the viscosity of solutions;
- form physical gels;
- stabilise dispersions and emulsions by adsorbing onto particles/droplets and inhibiting aggregation;
- induce particle aggregation to facilitate solid–liquid separation;
- modify surface properties to control wetting properties and inhibit deposition;
- solubilise hydrophobic compounds by complexation;
- facilitate the controlled release and delivery of active compounds.

This introductory chapter gives a brief overview of the key functional characteristics of water soluble polymers which are considered in more detail within the various chapters in this book.

## 1.1 Rheological behaviour

Water soluble polymers are able to form viscous solutions at concentrations of 1% or less and are widely used as thickeners in a broad range of products [1–7]. The viscosity of polymer solutions shows a marked increase at a critical polymer concentration commonly referred to as  $C^*$  which corresponds to the transition from the so-called ‘dilute region’, where the polymer molecules are free to move independently in solution without touching, to the ‘semi-dilute region’ where molecular crowding gives rise to the overlap of polymer coils and entanglement occurs. In the case of solid particles, the viscosity of spheres increases exponentially above a critical volume fraction of  $\sim 0.6$ , while for plate-like and rod-like particles the critical volume fraction is much lower. For polymer coils the viscosity only increases above a volume fraction of 1.0. The viscosity of polymer solutions is influenced significantly by the hydrodynamic volume of the polymer chains and hence is a function of shape, molecular mass, chain rigidity and electrostatic charge density. As will be discussed in

Chapters 2 and 3, polymer solutions normally exhibit Newtonian behaviour at concentrations well below  $C^*$ , i.e. their viscosity is not dependent on the rate of shear, however, above  $C^*$  non-Newtonian behaviour is usually observed. For most polymer-thickened systems, the viscosity–shear rate plot displays a high viscosity Newtonian plateau at low shear (typically at shear rates  $< 1/s$ ), a shear-thinning region (at shear rates  $\sim 1\text{--}10^2/s$ ) and a low viscosity plateau at high shear ( $> 10^2/s$ ). The magnitude of the viscosity at low shear determines the suspending properties. For example, xanthan gum has a very high low-shear viscosity and is now widely used in a variety of industries (e.g. food, pharmaceutical, agrochemicals, construction, etc.) to inhibit particle sedimentation and droplet creaming. Its other key feature is that it is highly shear thinning and so on stirring/pumping, etc. the viscosity decreases significantly enabling the product to flow. A classic example of its use is in the Food Industry in salad dressings. Even at very low concentrations the viscosity at low shear is such that xanthan can suspend herbs/spices but after shaking the bottle the dressing flows from the bottle. There are a range of polymer thickeners available commercially which include a number of natural polymers and their derivatives together with a range of synthetic polymers, largely acrylic based copolymers. The latter commonly have varying degrees of crosslinking and co-monomer types in order to control the viscosity–shear rate profile and solubility characteristics. For example, low degrees of crosslinking have the effect of increasing the molecular mass (and hence hydrodynamic volume) and consequently improve the thickening power. At high degrees of crosslinking the molecules are in the form of swellable microgels and the viscosity–volume fraction profiles are more similar to hard spheres rather than polymer coils. Copolymerisation of acrylics with surfactant monomers gives rise to so-called ‘associative thickeners’. The long alkyl chains incorporated into the polymer backbone or at the end of the polymer chains tend to associate through hydrophobic bonding in aqueous solution giving rise to the formation of weak three-dimensional networks which have a high low-shear viscosity but which are highly shear thinning.

As is discussed in Chapter 4 a number of water soluble polymers (mainly natural polymers) are able to form three dimensional gel structures, at very low concentrations ( $< 1\%$ ), by physical association of their polymer chains [2–6, 8]. This results in the formation of stable junction zones through, for example, hydrogen bonding (e.g. starch), hydrophobic association (e.g. high methoxy pectin), cation mediated crosslinking (e.g. pectin and alginate with calcium ions, guar gum and polyvinyl alcohol with borate ions), etc. In addition depending on the polymer, the gelation process may be triggered by increasing temperature (e.g. methylcellulose, hydroxypropylmethyl cellulose, polyethylene (PEO)–polypropylene (PPO) triblock copolymers) or decreasing temperature (e.g. agarose, carrageenan, gellan gum, gelatine). Gel formation only occurs above a critical minimum concentration,  $C_0$ , which is specific for each polymer. Below  $C_0$  precipitation may result.  $C_0$  is not the same as the critical overlap concentration,  $C^*$ , noted above. The properties of individual hydrocolloid gels vary considerably in strength and elasticity due to differences in the flexibility of the polymer chains, the number and nature of the junction zones and the degree of chain aggregation.

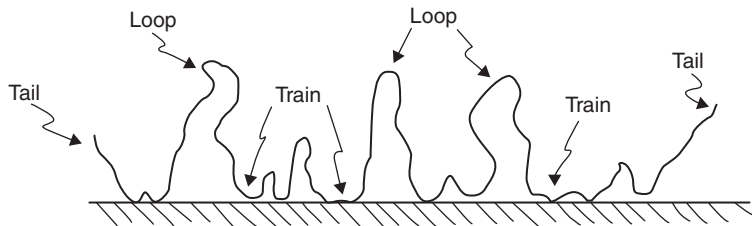
## 1.2 Polymer adsorption and colloid stability

Polymers will readily adsorb onto the surface of particles or droplets and are commonly used to control the stability and rheology of particulate dispersions and emulsions [9–12].

At low polymer additions the polymer molecules can rearrange at the surface and adsorb with a flat configuration with most of the segments in trains in contact or close to the surface. At higher polymer additions, where there is competition for surface sites, polymers adsorb with some of their segments in 'trains' and with some segments in 'loops' or 'tails' protruding away from the surface into solution (Figure 1.1). The proportion of trains to loops/tails depends on the energy of adsorption. Non-ionic polymers tend to adsorb with a significant proportion of their segments in loops and tails while polyelectrolytes can adsorb onto certain surfaces (through electrostatic interaction) with the majority of their segments in trains. Since polymers adsorb through many points of contact, the process is usually irreversible to dilution with the same solvent. The kinetics of adsorption is controlled by the rate of diffusion of the polymer molecules to the surface i.e., smaller molecules will adsorb initially. If the energy of adsorption is weak, namely through van der Waals forces (typical for adsorption of non-ionic polymers), molecular rearrangements can occur on the surface and the smaller molecules may be displaced by higher molecular mass molecules. If the energy of adsorption is strong, notably through electrostatic interaction (typical for polyelectrolytes) the small molecules cannot be displaced.

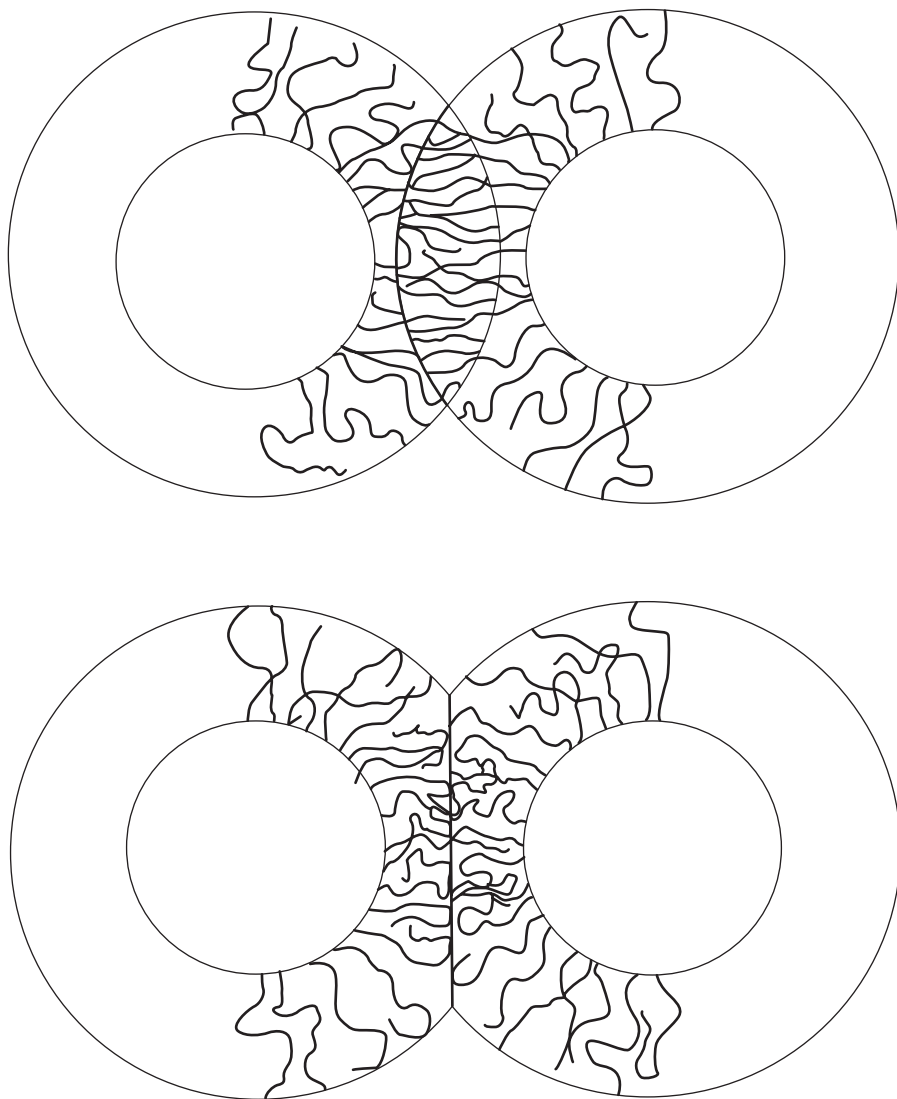
For charged polymers adsorbing onto particles of the same charge, the adsorbed polymer can increase the particle surface charge and hence inhibit particle aggregation by charge repulsions (electrostatic stabilisation) [9–13]. For example, low molecular mass sodium polyacrylate is commonly used to disperse clay and calcium carbonate used for coating high quality paper. Lower molecular mass polymers are preferred so that the viscosity of the dispersion does not increase significantly due to unadsorbed polymer in the continuous phase [14]. For certain applications, sulphonated polymers such as ligno-sulphonate are used as dispersants since unlike carboxyl- or phosphate-containing polymers they are not precipitated by the high concentrations of dissolved calcium ions.

In the case of polymers adsorbing onto particles of opposite charge, low additions of a relatively low molecular mass polymer may cause the particles to aggregate by reducing the net charge on the particles. In the case of very high molecular mass polymers (both non-ionic polymers and polyelectrolytes) particle aggregation can occur by the polymer adsorbing onto more than one particle simultaneously, so-called bridging flocculation. For example, polyacrylamides, (anionic, neutral or cationic) are commonly used in the treatment of industrial wastewater or sewage, where usually low ( $\leq 1\%$ ) volume fractions of solids need to be removed from water streams. The synthesis and properties of a range of polymeric flocculants are discussed in detail in Chapter 6.



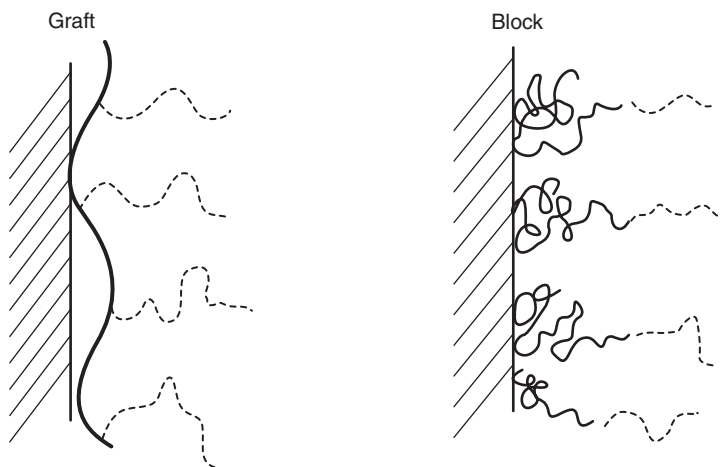
**Figure 1.1** Schematic illustration showing the adsorption of a polymer molecule onto a surface with varying proportions of segments in trains, loops and tails.

When the surfaces of particles are fully covered by polymer molecules, the extending layers can prevent aggregation by 'steric stabilisation' [9–13]. This arises from the increase in osmotic pressure (enthalpic contribution) and configurational constraints (entropic contribution) experienced by the segments when the adsorbed polymer layers overlap. Steric stabilisation will occur under good solvent conditions if the polymer layer extends out to a sufficient distance to prevent association through short range van der Waals attractive forces (Figure 1.2).



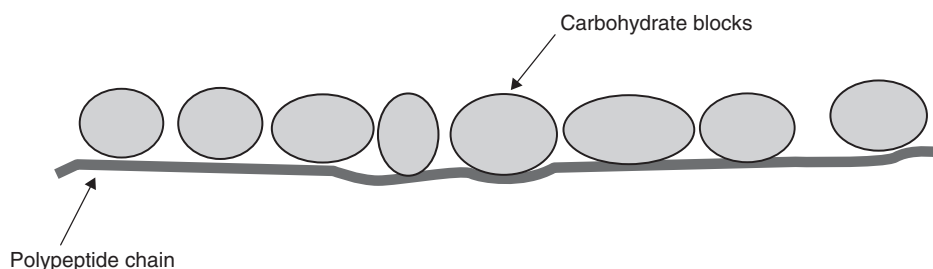
**Figure 1.2** Schematic representation of the repulsive forces giving rise to steric stabilisation. Top shows interpenetration of polymer layers giving rise to an increase in osmotic pressure in the overlap region and bottom shows compression of the polymer layers on close approach leading to a loss of configurational entropy.

A range of polymers with varying molecular architectures are nowadays used to confer steric stabilisation. Typical examples include graft (comb-like) and AB block copolymers (Figure 1.3). One of the components of the copolymer anchors the polymer chains to the surface while the other extends out into solution to provide a steric barrier. The chemical nature of each of the components can be selected to suit the particular need. Chapter 7 reviews the synthesis and solution properties of block and graft copolymers.



**Figure 1.3** Schematic representation of graft and block copolymers adsorbed on a surface.

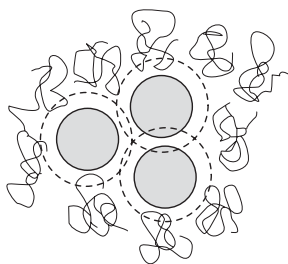
In the Food Industry the choice of stabiliser is restricted by legislation but there are a wide range of natural 'copolymers' to choose from, notably proteins and also certain polysaccharides such as gum Arabic. The latter consists of three molecular fractions, one of which has a 'wattle-blossom' type structure in which branched carbohydrate blocks are linked to a common polypeptide chain (Figure 1.4) [15]. Gum Arabic is widely used to stabilise concentrated flavour oils for application in beverages and it has been argued that the polypeptide anchors the molecules to the surface of the oil droplets while the carbohydrate blocks protrude out into solution and confer stability through electrostatic and steric mechanisms. There is considerable interest nowadays in forming polysaccharide–protein complexes to



**Figure 1.4** Schematic representation of the 'wattle-blossom structure' of one of the components of gum Arabic, which is responsible for its emulsification properties.

match the performance of gum Arabic. The role of proteins and polysaccharides in encapsulation and their influence in conferring emulsion stability is reviewed in Chapter 5.

The presence of non-adsorbed polymer in the continuous phase of particulate dispersions and emulsions can lead to weak particle/droplet aggregation by a volume restriction mechanism commonly referred to as depletion flocculation [10, 11, 13]. For example it has been shown that the addition of hydroxyethyl cellulose (0.08%) can lead to the aggregation of latex particles in paint formulations [16] and that the presence of xanthan gum at levels as low as 0.01% can induce the flocculation of emulsion droplets in mayonnaise and dressing formulations [17]. Depletion flocculation arises due to polymer molecules being excluded from the space between particles at short separations. This results in an osmotic pressure differential between the excluded region and the continuous phase leading to a net attractive force between particles (Figure 1.5). If the depletion force is greater than the sum of the electrostatic and steric repulsive forces, aggregation will occur.



**Figure 1.5** Schematic representation of the situation giving rise to depletion flocculation. Polymer molecules are excluded from the space between particles causing an osmotic pressure differential between the excluded region and the continuous phase and giving rise to a net attractive depletion force.

### 1.3 Surface modification

As polymers adsorb strongly to surfaces they can be used to change the surface energy and wetting characteristics. An example of this can be seen with the drainage of glass and crockery. After washing with surfactants and then rinsing in water the contact angle will be close to zero and a thin film of water will adhere to the plate. The film of water will evaporate with time leaving spots due to dust or salts present in the water. By adsorbing monolayers of hydrophilic polymers to the plate surface, the contact angle can be increased. With polymers that are slightly hydrophobic, the contact angle can be brought to about 30° and will facilitate the draining of the water film in a single sheet down the plate.

Polymers can also be used to prevent the adsorption of proteins to surfaces. For example, polyvinylpyrrolidone can prevent protein adsorbing onto a variety of surfaces and it can also displace adsorbed protein [18]. This has led, for example, to its application in the coating of filtration membranes in order to reduce biofouling. Polymers are also used to inhibit the adhesion of bacteria or water-borne micro-organisms onto surfaces [19, 20]. Bacteria are usually surrounded by exocellular polysaccharides that can aid adhesion to clean surfaces. Thus prosthetic devices and vascular implants carrying blood suffer from the build up of biofilms, leading to blockages and infection. This build up can be markedly reduced

by adsorbing a water soluble polymer on the surface. Typical polymers include polyethylene glycol (PEG) or PEG copolymers (e.g. PEG-acrylate). There is currently also much interest in using 'biocompatible polymers' such as hyaluronan to coat the surface of bio-materials [21]. As the micro-organism approaches the polymer-coated surface, segments of the exocellular polysaccharide and the surface-attached polymer overlap resulting in steric repulsion, thus inhibiting adsorption.

## 1.4 Complexation and controlled release

Many drugs, pesticides, dyes, etc. are hydrophobic in nature and hence are water insoluble. It has been shown that complexation or encapsulation of such active compounds with specific water soluble polymers can render them water soluble. A typical example is that of the complexation of hydrophobic compounds with polyvinylpyrrolidone. This polymer has a strong dipole, with a significant positive potential on one side of the polymer chain due to the amide nitrogen and a significant negative potential on the other due to the amide oxygen. The nitrogen is surrounded by hydrophobic methylene and methine groups while the oxygen is available to interact with solvent molecules [22]. Unlike other water soluble polymers, polyvinylpyrrolidone has the ability to dissolve in both water and organic solvents such as chloroform. Complexes between polyvinylpyrrolidone and water insoluble compounds can be produced by dissolving both the polymer and compound in chloroform and then removing the solvent by evaporation. The solid complex obtained can be instantly dissolved in water and this is illustrated in Figure 1.6 which shows the solubility of a hydrophobic dye, sudan red, alone and in the form of a complex with polyvinylpyrrolidone in water. At low polymer dye ratios (1:20) the dye is still completely insoluble. As the ratio increases (up to 2:1) some solubility is conferred but above this ratio the dye complex is completely soluble yielding optically clear solutions.

Further examples of polymers used to solubilise hydrophobic compounds are polyethylene oxide–polypropylene oxide–polyethylene oxide (PEO–PPO–PEO) triblock-type copolymers. Such polymers form micelles in solution with the more hydrophobic PPO chains forming the inner core and the more hydrophilic PEO chains the outer shell. Hydrophobic materials are able to dissolve within the core of the micelles and such systems are finding increasing



**Figure 1.6** Photograph showing the solubility of complexes formed between Sudan red and polyvinylpyrrolidone in water at varying polymer:dye ratios. The dye is insoluble in water at polymer:dye ratios of  $<2:1$  but is soluble at ratios of  $>4:1$ .



use in drug delivery. These are discussed in more detail in Chapter 7. Other polymeric systems, notably dendrimers, can also be used to solubilise compounds for drug delivery and other applications and their synthesis, properties are fully reviewed in Chapters 8. Another means of delivering active compounds is by encapsulating them within highly crosslinked polymer microgels. The microgels can be produced with a range of chemistries which enables them swell and contract by changing the solvent conditions (e.g. pH, ionic strength) and temperature. Active compounds within the matrix of the microgel are retained when the microgel is in its swollen state but are released when the microgel contracts. The synthesis, properties and applications of microgels are reviewed in Chapter 9.

## 1.5 Packaging

Water soluble polymers are also now finding application in the area of packaging. For example polyvinyl alcohol pouches are used to dispense liquid detergent formulations. The pouch is placed in the washing machine and the polyvinyl alcohol slowly dissolves to release the liquid. The emphasis nowadays is to use natural polymers, both polysaccharides and proteins, as packing materials because of their ability to biodegrade and recent advances in this area are covered in Chapter 10.

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## Chapter 2

# Natural Thickeners

*Graham Sworn*

## 2.1 Introduction

Natural thickeners can be defined as products obtained from natural sources such as plants, seeds, seaweeds and microorganisms. These products are high molecular weight polymers composed of polysaccharides and are often referred to as hydrocolloids. Production processes vary from simple collection of tree exudates and milling in the case of gum arabic to more complex production by fermentation as in the case of xanthan gum. A number of these natural thickeners are also derivatised in order to modify their properties. Table 2.1 provides a simple classification of these products by source. Tables 2.2–2.4 provide an overview of the main natural thickening agents and their applications. A brief description of each class of hydrocolloids is given below but for more detailed information on each of the hydrocolloids there are a number of publications available [1–3].

### 2.1.1 Marine polysaccharides

This group includes the carrageenans, a group of sulphated galactans, which are extracted from red seaweed (Rhodophyceae) species such as *Eucheuma cottonii*, *Eucheuma spinosum*, *Chondrus crispus* and *Gigartina* species. The carrageenans are split into three main types according to their ester sulphate content. These are lambda, iota and kappa in the order of decreasing ester sulphate content. The carrageenan type varies according to the weed source. Lambda carrageenan is a non-gelling thickener whereas iota and kappa types are gelling.

**Table 2.1** Classification of polysaccharides

Marine	Botanical	Microbial	Chemically modified
Carrageenans	Guar gum	Xanthan gum	Cellulose gums
Agar-agar	Locust bean gum	Gellan gum	Modified starches
Alginates	Gum tragacanth	Pullulan	Propylene glycol alginate
	Konjac glucomannan	Curdlan	Modified guar gum
	Tara gum	Dextran	
	Cassia gum	Welan gum	
	Gum arabic	Rhamsan	
	Pectin	Succinoglycan	
	Starches		

Table 2.2 Summary of natural thickeners

Product	E number	Origin	Source	Region	Constituent sugars	Applications
Guar gum	E 412	Seed	<i>Cyamopsis tetragonolobus</i>	India, Pakistan	L-mannose, D-galactose	Drinks, sauces, soups, ketchups, dressings, flour additive
Locust bean gum (LBG, Carob)	E 410	Seed	<i>Ceratonia siliqua</i>	Spain, Morocco, Portugal	L-mannose, D-galactose	Ice cream, hot prepared sauces, soups, ketchups, dressings
Tara gum	E 417	Seed	<i>Caesalpinia spinosa</i>	Peru, Ecuador	Galactomannan	Sauces, soups, ketchups, dressings
Cassia gum	E 499	Seed	<i>Cassia tora</i> , <i>Cassia obtusifolia</i>	Sub-tropical	Galactomannan	Pet foods
Karaya	E 416	Plant exudate	<i>Sterculia urens</i>	India, Senegal, Mali	D-galacturonic acid, L-rhamnose, D-galactose, D-glucuronic acid	Brown sauce, coatings, fillings, toppings, chewing gum
Gum Tragacanth	E 413	Plant exudate	<i>Astragalus</i> species	Iran, Turkey	L-arabinose, D-galactose, D-galacturonic acid, L-rhamnose	Confectionery icings, dressings, flavour oil emulsions
Gum Arabic (Acacia gum)	E 414	Tree exudate	<i>Acacia senegal</i> , <i>saya</i>	Sudan	D-galactose, D-glucuronic acid, L-rhamnose/L-arabinose	Drinks, confectionery gums, adhesives
Konjac	E 425-i-ii	Tuber	<i>Amorphophallus konjac</i>	Far East	D-mannose, D-glucose	Desserts, aspics, surimi, frozen desserts, sauces, batters
Xanthan gum	E 415	Microbial	<i>Xanthomonas campestris</i>	USA, Europe, China	D-glucose, mannose, glucuronic acid	Sauces, dressings, drinks, fruit preparations, cakes, desserts, meat products, cosmetics, cleaners, oil drilling
Succinoglycan	Not permitted in food (except Japan)	Microbial	<i>Agrobacterium tumefaciens</i>	Europe, Japan	Galactose, Glucose	Acidic cleaners, Food products (Japan only)
Welan gum	Not permitted in food	Microbial	<i>Alcaligenes</i> species	USA	D-glucose, glucuronic acid, L-rhamnose, mannose	Tyre sealants, de-icing fluids, pigment suspensions for concrete
Rhamsan gum	Not permitted in food	Microbial	<i>Alcaligenes</i> species	USA	D-glucose, glucuronic acid, L-rhamnose	Cleaners
Sodium alginate	E 401–E 404	Brown seaweeds	<i>Laminaria</i> , <i>Macrocystis</i> , <i>Ecklonia</i> , <i>Lessonia</i> species	North/South America, Europe, Australia, Africa	Mannuronic acid, guluronic acid	Sauces, salad dressings, desserts, fruit preparations, ice cream, water ices, onion rings, low fat spreads, bakery filling creams, fruit pies, textile printing, paper industry
Pectin (high and low ester)	E 440	Fruit	Citrus, apple, sugar beet, sunflower	North/South America, Europe	Galacturonic acid, rhamnose, galactose, arabinose	Jams, confectionery, bakery fillings, toppings, fruit preparations, glazes, sauces, water ices, sorbets, yogurt drinks

**Table 2.3** Summary of derivatives of natural thickeners

Product	E number	Base material	Reactant	Applications
Carboxymethyl guar	Not permitted in food	Guar gum	Sodium monochloroacetate	Printing pastes (reactive dyestuffs)
Hydroxypropyl guar	Not permitted in food	Guar gum	Propylene oxide	Cosmetics, textile finishing
Phosphated guar	Not permitted in food	Guar gum	Sodium dihydrogen phosphate	Paper products
Cationic guar	Not permitted in food	Guar gum	2'3'-epoxypropyl-trimethyl ammonium chloride	Hair and skin care products, paper manufacture, waste water clarification
Propylene glycol alginate (PGA, propane 1,2-diol alginate)	E405	Alginic acid	Propylene oxide	Salad dressings, meringues, ice cream, noodles, fermented milk drinks, dairy desserts, beer
Carboxyl methyl cellulose (CMC)	E 466	Cellulose	Monochloroacetic acid	Drinks, dairy drinks, powdered drinks, sauces, dressings, ice cream, water ices, bakery products, low pH dairy products, cosmetics, paper, textiles, oil drilling, adhesives
Hydroxypropyl cellulose (HPC)	E 463	Cellulose	Chloromethane and propylene oxide	Aerated toppings
Hydroxypropylmethyl cellulose (HPMC)	E 464	Cellulose	Propylene oxide	Soya burgers, sausages, onion rings, potato croquettes, waffles, batters, coatings, doughnuts, gluten free bakery products, shampoo, lotions
Methyl cellulose	E 461	Cellulose	Chloromethane	Soya burgers, sausages, onion rings, potato croquettes, waffles, batters, coatings, doughnuts, gluten free bakery products, building materials
Methyl ethyl cellulose (MEC)	E 465	Cellulose	Chloromethane and chloroethane	Non-dairy creams, toppings, aerated desserts, mousses, meringues, mallows, batters
Amidated pectin	E 440ii	High ester pectin	Ammonia	Jams, confectionery, bakery fillings, toppings, fruit preparations, glazes, sauces, water ices, sorbets, yogurt drinks

**Table 2.4** Summary of starch derivatives

Product	E Number	Applications
Oxidised starch	E 1404	Confectionery, dairy products, batters and breadings, coatings
Monostarch phosphate	E 1410	Frozen gravies, pie fillings, dressings
Distarch phosphate	E 1412	Sauces, dressings, dry mix puddings, baked goods
Phosphated distarch phosphate	E 1413	Sauces, frozen gravies, pie fillings
Acetylated distarch phosphate	E 1414	Soups, sauces, dairy products, fruit fillings, pet foods, chilled and frozen meals
Acetylated starch	E 1420	Batters, breadings, snacks, cereals, confectionery
Acetylated distarch adipate	E 1422	Gravies, sauces, dressings, sweet and savoury fillings, fruit preparations, dairy products, chilled and frozen meals
Hydroxypropyl starch	E 1440	Meat, beverages, low-fat and low-calorie foods
Hydroxypropyl distarch phosphate	E 1442	Gravies, soups, sauces, dressings, sweet and savoury fillings, fruit preparations, dairy products, chilled and frozen meals, meat
Starch sodium octenylsuccinate	E 1450	Spray dried flavours, beverage emulsions, emulsified sauces, dressings

Iota forms soft, thixotropic gels in the presence of calcium whereas kappa forms firm, brittle gels in the presence of potassium or to a lesser extent calcium.

Alginates are extracted from brown seaweed (Phaeophyceae) species such as *Macrocystis pyrifera*, *Laminaria hyperborea* and *Ascophylum nodosum*. Alginates are block copolymers composed of manuronic acid (M) and guluronic acid (G) residues. The ratio of these substituents, the M/G ratio is dependent on the weed source and the part of the weed used. M/G ratio also governs the properties of the alginate. Sodium salts of alginate are soluble in water and are used as thickeners and gelling agents. Gelation occurs through addition of calcium. Alginates rich in manuronic acid residues (high M) form softer more flexible gels with little or no syneresis compared to their guluronic-acid-rich (high G) counterparts.

Agar is a collective term for a complex mixture of polysaccharides which are extracted from *Gelidium* and *Gracilaria* species of red seaweed. Agarose, a neutral polymer, and agarpectin, a charged sulphated polymer, are the two major fractions. Agar typically forms firm, brittle gels on cooling and show thermal hysteresis. It is used extensively in microbiological media and confectionery products.

### 2.1.2 Botanical polysaccharides

This is perhaps the most diverse group of polysaccharides. Many of these materials have been known to man for centuries. Guar gum, locust bean gum (LBG), tara and cassia gum are composed of a (1 → 4) linked mannose backbone with single galactose substituents and are therefore referred to as galactomannans. They differ in the degree of galactose substitution,

guar typically containing one galactose per every two mannose residues whereas LBG typically has only one galactose every four to five residues. All the galactomannans are thickeners and their properties, such as solubility and interaction with xanthan or carrageenan, are governed by the galactose content. For example, guar is soluble in cold water whereas LBG must be heated to  $\sim 90^{\circ}\text{C}$  to hydrate. LBG, under certain conditions, will form soft flexible gels with xanthan whereas guar only shows a synergistic increase in viscosity. Tara and cassia gum have properties intermediate to those of guar and LBG.

Pectins are extracted from a variety of sources including apples and citrus fruits. They are composed of galacturonic acid residues with occasional rhamnose interruptions. They are usually classified in terms of their degree of methyl esterification. Low ester ( $<50\%$ ) pectins gel in a similar way to alginates through reaction with calcium. High ester ( $>50\%$ ) pectins require low pH and high soluble solids ( $>\sim 55\%$ ) to gel. Under these conditions intermolecular electrostatic repulsions are reduced. The type of solids has an effect on the gels. For example, sucrose is more effective at promoting gelation than corn syrup. This class of polysaccharides also includes the starches and gum arabic.

### 2.1.3 Microbial polysaccharides

There have been many microbial polysaccharides produced by fermentation including, dextran, welan, rhamsan, pullulan, curdlan and scleroglucan that have caught the imagination of the academics and industrialist alike. However, very few have found widespread use industrially. The notable exception to this is xanthan gum. It is produced during fermentation by the organism *Xanthomonas campestris*. Its primary structure is a linear  $(1 \rightarrow 4)$  linked  $\beta$ -D-glucose backbone (as in cellulose) with a trisaccharide side chain on every other glucose, containing a glucuronic acid residue linked  $(1 \rightarrow 4)$  to a terminal mannose unit and  $(1 \rightarrow 2)$  to a second mannose that connects to the backbone. The terminal mannose is pyruvylated and the non-terminal residue carries an acetyl group. Xanthan gum is soluble in cold water and is an extremely effective thickener. It also interacts synergistically with the galactomannans.

### 2.1.4 Chemically modified polysaccharides

This group includes the chemically modified cellulose products such as carboxymethyl cellulose (CMC), hydroxypropylmethyl cellulose (HPMC) and hydroxyethyl cellulose (HEC). The purpose of these modifications is primarily to render the basic cellulose backbone soluble. In this way a range of cellulose-based products are produced with a variety of functions from thickening in the case of CMC to thermogelation in HPMC. Similarly, there are a wide variety of chemically modified starches available including hydroxyethyl and hydroxypropyl. These modifications to the native starch improve stability to heat and to acid, improve processing and reduce the tendency to retrogradation. Alginates are also modified by esterification with propylene glycol to produce propane 1,2-diol alginate (PGA). This modification makes the alginates less sensitive to precipitation by acid and calcium which enables the PGA to remain in solution below pH 4.0. Chemically modified guar gums are also available commercially for non-food applications. Modifications include carboxymethylation to improve alkali compatibility, hydroxyalkylation to improve solubility and compatibility

**Table 2.5** Functionality of natural thickeners

Function	Example
Adhesive	Glazes, icings, frostings, wall paper paste
Binding agent	Pet foods
Bodifying agent	Dietetic beverages
Crystallisation inhibitor	Ice cream, sugar syrups, frozen foods
Clarifying agent (fining)	Beer, wine
Cloud agent	Fruit drinks, beverages
Coating agent	Confectionery, fabricated onion rings
Dietary fibre	Cereals, bread
Emulsifier	Salad dressings
Encapsulating agent	Powdered flavours
Film former	Sausage casings, protective coatings, paper sizing
Flocculating agent	Wine
Foam stabiliser	Whipped toppings, beer
Gelling agent	Puddings, desserts, confectionery
Moulding	Gum drops, jelly candies
Protective colloid	Flavour emulsions
Stabiliser	Salad dressings, ice cream, cosmetics
Suspending agent	Chocolate milk, drilling fluids
Swelling agent	Processed meat products
Syneresis inhibitor	Cheese, frozen foods
Thickening agent	Jams, pie fillings, sauces, toilet cleaners, cosmetics
Whipping agent	Toppings, marshmallows

with electrolytes, phosphatisation to cross-link the guar and improve the film-forming properties and cationisation to create a cationic guar gum for use in conditioning shampoos and cosmetic preparations.

Natural thickeners and their derivatives are used in many different industries including food, oil drilling, paper coating, pesticides, textile and carpet printing, cosmetics, personal care and pharmaceuticals. A casual glance at the labels in any supermarket will very quickly reveal the diversity of products containing these versatile thickeners. They are found in salad dressings, ice cream, confectionery, soups and sauces, toilet cleaners, and shampoo for example. Technical literature on hydrocolloids from suppliers and academics alike also testify to the wide range of functional properties they bring to an application (Table 2.5) [1]. It is also evident that most of these functional properties have at one time or another been associated with all of the commercial hydrocolloids. There is a great deal of overlap between different hydrocolloids in terms of functionality and application but it is also true that each of the hydrocolloids tends to excel in a few specific areas. Much of the functionality associated with natural thickeners can be related to the rheological behaviour.

## 2.2 Introduction to rheology

Rheology is the science of flow and deformation of matter and is considered a branch of physics. The flow of materials has been a concern since the earliest times. Lucretius, a



Roman poet and philosopher born at the beginning of the 1st century BC, wrote in his poem *De Rerum Natura* (*On the nature of things*):

For water moves and flows with so very small a moving power because it is made of small rolling shapes. But on the other hand, the nature of honey has more cohesion, its fluid is more sluggish, and its movement more tardy, for the whole mass of its matter coheres more closely assuredly because it is not made of bodies so smooth or so delicate and round.

The modern science of rheology can be traced back to the formation of the Society of Rheology and the founding of the *Journal of Rheology* in 1928. This was initiated by Prof. E.C. Bingham. In fact, Prof. Bingham is referred to as the 'Founder of Modern Rheology' in Scott Blairs book of 1938, *An Introduction to Industrial Rheology*, which constitutes the first comprehensive British text on the subject [4].

The science of rheology encompasses the behaviour of both solid and liquid materials. This extends from a perfectly elastic solid, defined by Robert Hooke in 1678, to a perfectly viscous liquid, defined by Newton in 1687, and to the myriad of viscoelastic materials in between. The rheology of natural thickeners is primarily concerned with viscosity and viscoelasticity.

### 2.2.1 Measurement of viscosity

The viscosity of a fluid is a measure of the frictional resistance it offers to an applied shearing force. Figure 2.1 shows two parallel planes in a fluid, separated by a distance ( $dx$ ) and having velocities of flow differing by ( $dv$ ). According to Newton's law of viscous flow, the frictional force ( $F$ ), resisting the relative motion of two adjacent layers in the liquid, is proportional to the area ( $A$ ) and the velocity gradient ( $dv/dx$ ):

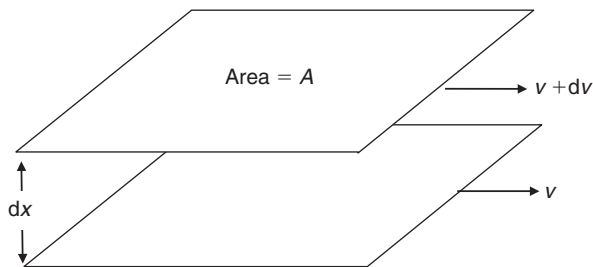
$$F = \eta A(dv/dx) \quad (2.1)$$

The proportionality constant ( $\eta$ ) is known as the coefficient of viscosity or simply as viscosity.

This equation is more typically in the form:

$$\sigma = \eta \dot{\gamma} \quad (2.2)$$

where the shear stress ( $\sigma$ ) is equivalent to the force per unit area ( $F/A$ ) and the shear rate ( $\dot{\gamma}$ ) is the velocity gradient ( $dv/dx$ ). In other words, the viscosity is equal to the shear stress divided by the shear rate.



**Figure 2.1** The definition of the coefficient of viscosity ( $\eta$ ). Two parallel layers of fluid, of area  $A$ , are separated by a distance  $dx$ , and the difference in their velocities is  $dv$ .

There are generally two approaches to the measurement of viscosity namely, controlled stress and controlled strain. In controlled stress, a known stress is applied to the fluid and the resultant shear rate is measured. Conversely, in controlled strain a known strain, or more accurately rate of strain (shear rate) is applied and the stress is measured. A falling ball viscometer is a controlled stress viscometer in which the applied stress comes from the size of the ball and gravity whereas the Brookfield viscometer is an example of a controlled strain instrument where the rate of strain is related to the rotational speed applied.

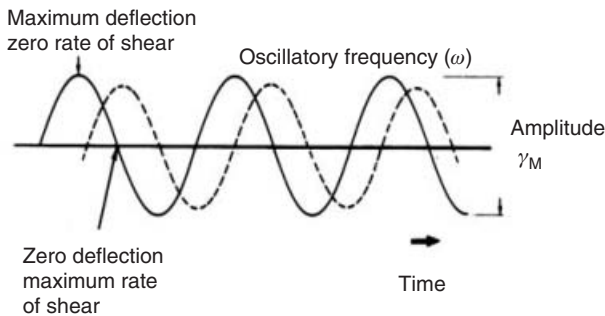
### 2.2.2 Measurement of viscoelasticity

Newton's law of viscous flow and Hooke's law for solids describe the perfect state for each. In practice however, few if any materials show this ideal behaviour and are more appropriately described as viscoelastic. That is to say, they exhibit both viscous and elastic behaviour. More importantly, the relative contribution of each with regard to a materials response will depend on the time scale of the experiment. If the experiment is relatively slow the material will appear viscous. Conversely, if the experiment is relatively fast the material will appear more elastic.

Mechanical spectroscopy is an ideal technique for investigation of the viscoelastic properties of materials. It involves the application of a sinusoidal oscillation of strain ( $\gamma$ ) and frequency ( $\omega$ ) to the material. A perfectly elastic material will have a stress wave exactly in phase with the applied strain wave. A purely viscous material will have a stress wave exactly  $90^\circ$  out of phase with the applied strain since at the maximum deflection the rate of strain (shear rate) is zero. This is illustrated in Figure 2.2 [5].

Typically the stress wave will have a phase difference ( $\delta$ ) between  $0^\circ$  and  $90^\circ$ . The in-phase and out-of-phase components of the stress wave can be separated to give the elastic or storage modulus ( $G'$ ) and the viscous or loss modulus ( $G''$ ). These can be calculated from the expression:

$$G^* = \tau^*/\gamma_0 = \sqrt{G'^2 + G''^2} \quad (2.3)$$



**Figure 2.2** Sinusoidal oscillatory shear. At the extremes of the oscillatory cycle shear strain  $\gamma$  (solid) is maximum, but shear rate  $\dot{\gamma}$  (dotted) is zero, while the converse is the case at the null strain position (from Ref. [5]).

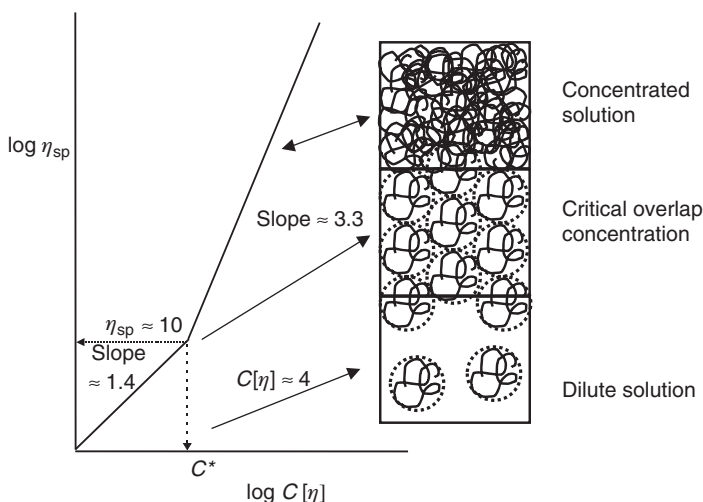
where  $\tau^*$  is the complex shear stress,  $\dot{\gamma}_0$  is the maximum strain and their ratio is the complex shear modulus ( $G^*$ ). The complex dynamic viscosity ( $\eta^*$ ) is equal to  $G^*/\omega$  and  $\tan \delta$  is the ratio of  $G''/G'$ .

## 2.3 Rheology of natural thickeners

In general, polymer gels and networks can be divided into three categories according to the nature of the interactions between the polymer chains:

- (1) Covalent cross-linked networks
- (2) Physical networks
- (3) Entanglement networks.

The majority of natural polysaccharides fall into categories 2 and 3. In category 2, the polysaccharides are physically cross-linked through such mechanisms as hydrogen bonding, or cation-mediated junction zones to form networks and these polysaccharides are often referred to as gelling agents. Thickeners generally fall into category 3. In the case of entanglement networks, in which no enthalpic polymer–polymer interactions are observed, properties very much related to the size and number of molecules in solution, i.e. molecular weight and concentration and the concept of space occupancy (hydrodynamic volume), become important [6, 7]. In dilute solution the individual molecules (random coils) are free to move independently. As the concentration is increased the molecules begin to come into contact with one another. The motion of the molecules becomes restricted and the system can be visualised as a sea of entangled spaghetti. This transition from free-moving molecules to an entangled network is accompanied by a change in the concentration dependence of the viscosity as shown schematically in Figure 2.3. The concentration of polysaccharide at which the change occurs is referred to as the critical overlap concentration and is denoted as  $C^*$ . Intrinsic viscosity  $[\eta]$  can be used to



**Figure 2.3** Generalised concentration dependence of viscosity for random coil polysaccharides.

compare the dilute solution viscosities of hydrocolloids [8]. The intrinsic viscosity will depend on the size and shape of the polymer molecule. The onset of entanglement for a wide range of neutral and charged polysaccharides is found to occur when  $C[\eta] \cong 4$  (i.e.  $C^* \cong 4/[\eta]$ ). In other words, the higher the intrinsic viscosity of the polysaccharide, the lower the concentration at which  $C^*$  is exceeded. Hydrodynamic volume is also important. The greater the hydrodynamic volume the lower the concentration required to exceed  $C^*$ . A number of factors will influence this [8]. Chain stiffness and branching will influence the hydrodynamic volume. The stiffer the chains the larger the volume occupied. Branched polymers will be more compact than linear polymers of the same molecular weight and will therefore have a lower hydrodynamic volume. The solvent also has an effect. The higher the quality of the solvent for the polymer, the greater the hydrodynamic volume will be. In a good solvent, interactions between the polymer and the solvent will be favoured at the expense of polymer–polymer interactions. Generally, ionic polymers will be more expanded than non-ionic polymers due to electrostatic repulsion between like charges. Increasing the ionic strength of the solution will decrease this effect.

It is generally recognised that a further distinction can be made for polysaccharide networks and gels, namely [6, 9]:

- (1) Entanglement network solutions
- (2) Weak gels
- (3) Strong gels.

The above classification is based on the measurement of both steady and oscillatory rheological behaviour. This classification of networks and gels has been widely adopted by many in the field of polysaccharide rheology. However, it was never intended to be absolute but rather to be treated as a useful but artificial division [10]. For example, xanthan rheology is often attributed to its weak gel network yet in many instances has a measurable lower Newtonian viscosity ( $\eta_0$ ).

### 2.3.1 Viscosity of entanglement network solutions

For entanglement networks a distinction between the behaviour above and below  $C^*$  must also be made. Polysaccharide solutions below  $C^*$  will typically exhibit near Newtonian steady shear flow and the increase in the viscosity of the solvent is roughly proportional to the number of molecules present. In general, a doubling of concentration will increase viscosity by a factor of  $\sim 2.5$ . Above  $C^*$  entanglement network solutions will exhibit shear-thinning (pseudoplastic) flow as a function of shear rate. The viscosity falls as shear rate is increased. The concentration dependence of viscosity increases and generally a doubling of polymer concentration above  $C^*$  will result in an approximately tenfold increase in viscosity [6, 7].

Figure 2.4 illustrates a generalised plot of the viscosity versus shear rate for a polysaccharide entanglement network ( $C > C^*$ ). At low shear rates the shear rate dependence of viscosity is Newtonian since the disentanglement due to shear is slower than or equal to the formation of new entanglements. This is known as the zero shear or lower Newtonian viscosity, denoted as  $\eta_0$ . As shear rate is increased, the rate of disruption also increases and exceeds that of formation. At this point viscosity begins to decrease sharply as a function of shear rate. This is known as the shear-thinning or pseudoplastic region. Eventually, at very high shear rates no further disruption can take place and the system once again exhibits

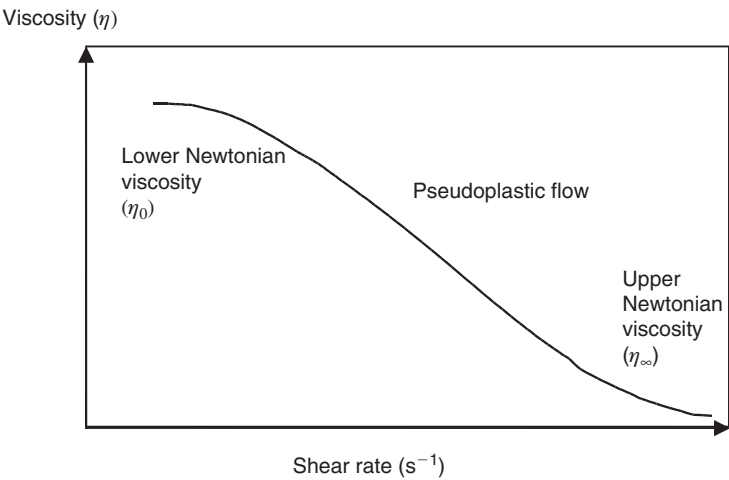


Figure 2.4 Idealised flow curve of an entanglement solution of a polysaccharide.

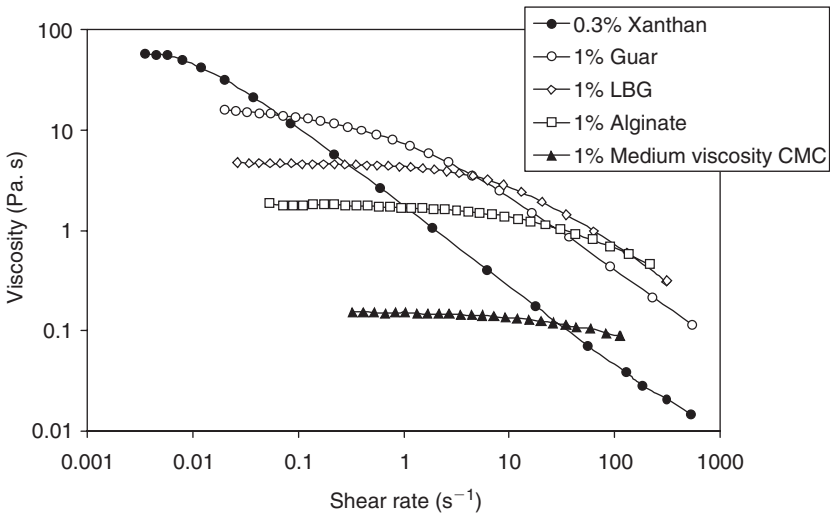


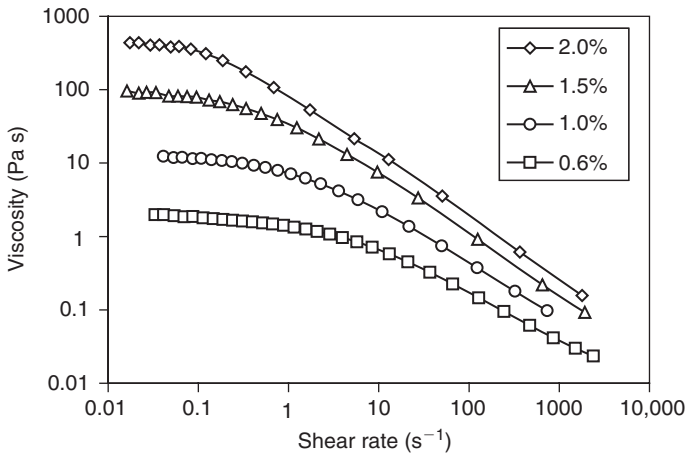
Figure 2.5 Flow curves for various hydrocolloid thickening agents in 1% NaCl.

Newtonian flow. This is called the infinite shear or upper Newtonian viscosity, denoted as  $\eta_{\infty}$ . This flow behaviour can be accurately modelled using the Cross equation [11]:

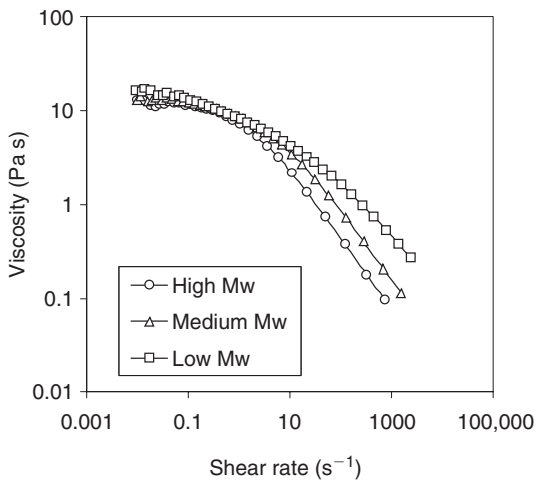
$$\eta = \eta_{\infty} + (\eta_0 - \eta_{\infty}) / (1 + k\dot{\gamma}^n) \tag{2.4}$$

where  $\eta_0$  and  $\eta_{\infty}$  are the zero and infinite shear viscosity, respectively,  $k$  is a constant parameter with the dimension of time and  $n$  is a dimensionless constant.

Entanglement solutions of the various polysaccharides differ greatly in the magnitude of their zero shear viscosity and in the shear rate at which shear thinning commences



**Figure 2.6** Effect of concentration on flow behaviour of guar gum solutions in deionised water.



**Figure 2.7** Effect of molecular weight on the flow properties of guar gum solutions in deionised water (high Mw =  $2.66 \times 10^6$  g/mol, 1.0% guar gum; medium Mw =  $1.43 \times 10^6$  g/mol, 1.5% guar gum; low Mw =  $4.23 \times 10^5$  g/mol, 4% guar gum).

(Figure 2.5). The degree of pseudoplasticity for a given hydrocolloid will increase with an increase in the concentration and molecular weight. Figure 2.6 illustrates this with guar gum. As the concentration is increased both the degree of pseudoplasticity and the zero shear viscosity increase. Figure 2.7 shows that when the concentration of the guar gum solution is adjusted to give similar zero shear viscosity, the pseudoplasticity decreases with decreasing molecular weight. However, it has been demonstrated that the form of shear-thinning behaviour is a general phenomenon [12]. Morris and co-workers showed that, by expressing measured viscosity as a fraction of the zero shear viscosity ( $\eta/\eta_0$ ) and applied shear rate relative to the shear rate required to reduce viscosity to a fixed fraction of  $\eta_0$  ( $\dot{\gamma}/\dot{\gamma}_f$ ), a wide range of

entanglement solutions of polysaccharides of differing primary structure, molecular weight and concentration collapse onto a single master curve.

Few if any commercial instruments are capable of measuring a broad enough shear rate range to see the whole flow curve of a polysaccharide solution, and in practice it is more typical to see perhaps the lower Newtonian region and the onset of shear-thinning behaviour. The origin of shear thinning in macromolecular solutions is believed to be caused by the following factors, one or more of which may apply to a particular solution:

- (1) increased orientation of asymmetric molecules with shear rate;
- (2) change in the shape of flexible molecules with shear;
- (3) effect of flow on intermolecular interactions.

The shear-thinning region of flow can be conveniently modelled with a power law equation of the form:

$$\tau = k\dot{\gamma}^n \quad (2.5)$$

where  $\tau$  is the applied stress,  $\dot{\gamma}$  is the shear rate and  $k$  and  $n$  are constants often referred to as the consistency index and flow index, respectively. The flow index ( $n$ ) can be particularly instructive since it is a measure of the degree of pseudoplasticity. A value of 1 would indicate Newtonian flow. Whilst the power law model does have some utility in the practical interpretation of rheology clearly it is not sufficient to fully characterise the flow behaviour of polysaccharides. The constants  $k$  and  $n$  are very much dependent on the concentration and shear rate range within which the measurements are made. As indicated previously the Cross model is a much more accurate representation of the flow behaviour of polysaccharides. Equation (2.4) can be simplified by regarding  $\eta_\infty$  as negligible [6]:

$$\eta = \eta_0 / (1 + k\dot{\gamma}^n) \quad (2.6)$$

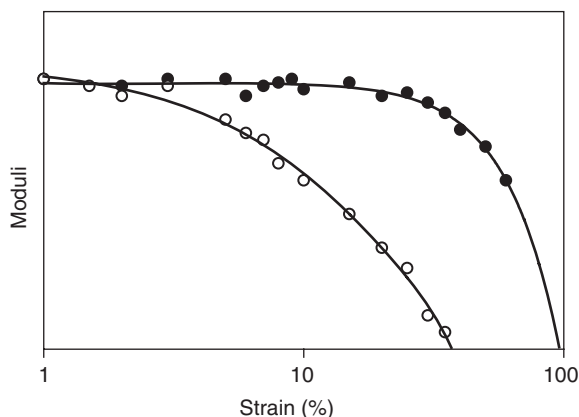
This expression can be further simplified for random coil polysaccharide solutions above  $C^*$  since the fitting of equation 2.6 to the master curve of  $\eta/\eta_0$  versus  $\dot{\gamma}/\dot{\gamma}_f$ , where  $f = 0.1$  yields the values of 18 and 0.76 for  $k$  and  $n$ , respectively. Therefore:

$$\eta = \eta_0 / (1 + (18\dot{\gamma}/\dot{\gamma}_{0.1})^{0.76}) \quad (2.7)$$

Using equation (2.7) the shear-thinning behaviour of any entanglement polysaccharide solution can be characterised by two parameters, the zero shear viscosity and the shear rate required to reduce viscosity to some fraction of  $\eta_0$ . This can be conveniently set to  $\dot{\gamma}_{1/2}$  [7].

### 2.3.2 Viscoelasticity of entanglement network solutions

Initially, for characterisation by mechanical spectroscopy, the strain dependence of, for example, the complex shear modulus ( $G^*$ ) is established. Typical results are shown schematically in Figure 2.8. This experiment establishes the linear viscoelastic region of the system, within which the viscoelastic functions are independent of strain. In other words, the applied strain does not perturb the sample. For entanglement networks the linear viscoelastic region extends to approximately 25% strain.



**Figure 2.8** Strain dependence of an entanglement solution or strong gel (●) and weak gel (○).

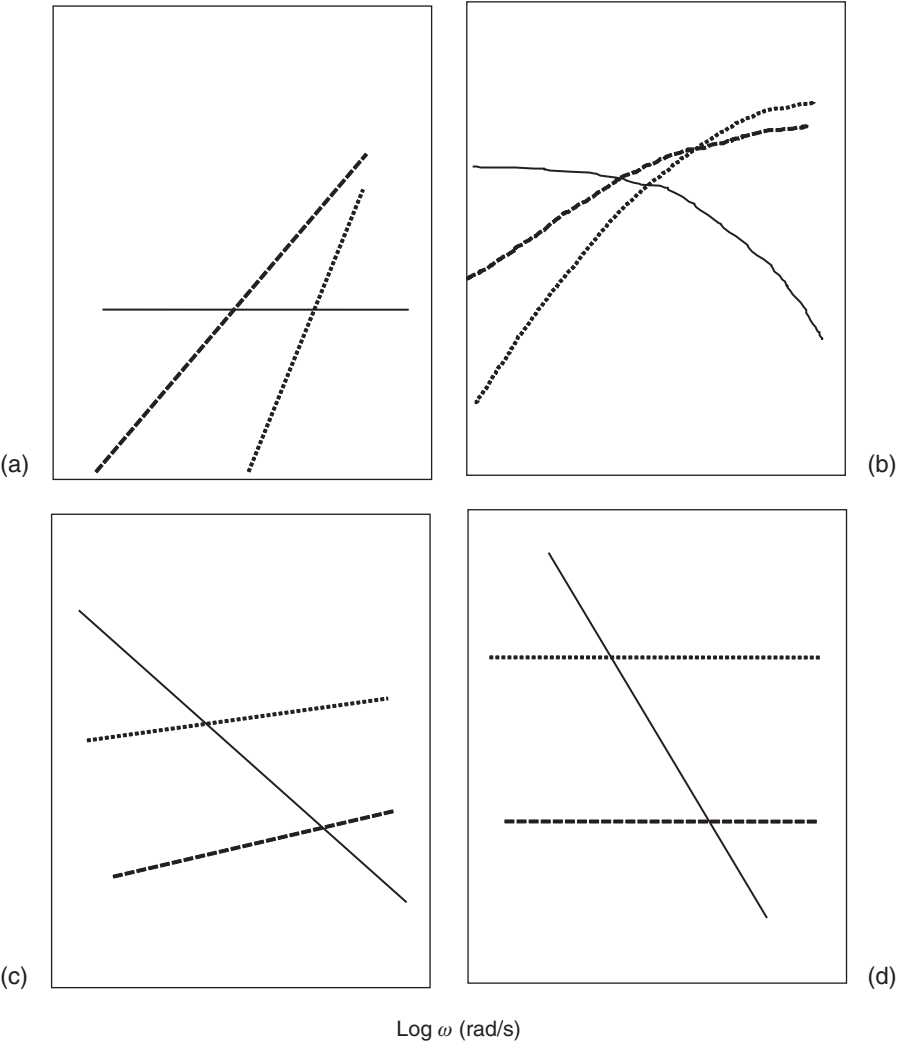
The system can be further characterised by measurement of the mechanical spectrum at a strain within the linear viscoelastic region defined by the strain sweep. Here the storage ( $G'$ ) and loss ( $G''$ ) modulus, and complex viscosity ( $\eta^*$ ) are measured as a function of frequency ( $\omega$ ) and plotted on double logarithmic plots. Typical mechanical spectrum of entanglement solutions are shown in Figure 2.9.

Figure 2.9a and b compares the mechanical behaviour below and above  $C^*$ , respectively. Below  $C^*$  both moduli are strongly dependent on frequency ( $\omega$ ) with typically  $G' \propto \omega^2$  and  $G'' \propto \omega$ . Complex viscosity ( $\eta^*$ ) shows little dependence on frequency. Above  $C^*$  where entanglement networks are formed, the mechanical spectrum at the low-frequency end is similar to that below  $C^*$  since the time scale of the measurement is long by comparison to the time scale of the molecular motions. At higher frequencies where the experimental time scale is shorter than the molecular rearrangements the mechanical spectrum resembles that of a gel:  $G' > G''$ , with little dependence on frequency and  $\eta^*$  decreasing with increasing  $\omega$ . These systems also obey the Cox–Merz superposition principal [13]. That is, complex viscosity as a function of frequency  $\eta^*(\omega)$  rad/s will superimpose on a plot of steady shear viscosity versus shear rate  $\eta(\dot{\gamma})$ /s over the same range of  $\omega$  and  $\dot{\gamma}$ . In other words, the viscosity measured in a non-destructive way (oscillation) is the same as the viscosity measured in a destructive way (flow).

### 2.3.3 Weak and strong gels

The strain dependence of weak and strong gels is shown in Figure 2.8. The strain dependence of the viscoelastic functions of strong gels is very similar to entanglement solutions with the linear viscoelastic region extending to approximately 25% strain. For weak gels this region is typically less than 5% strain, xanthan being a classic example. Weak and strong gels, as shown in Figure 2.9c and d respectively, exhibit a very similar mechanical spectrum:  $G'$  is significantly higher than  $G''$  throughout the frequency range and both moduli show little or no dependence on frequency. The complex viscosity decreases with increasing frequency with a slope approaching  $-1$ . However, they can be distinguished on the basis of their

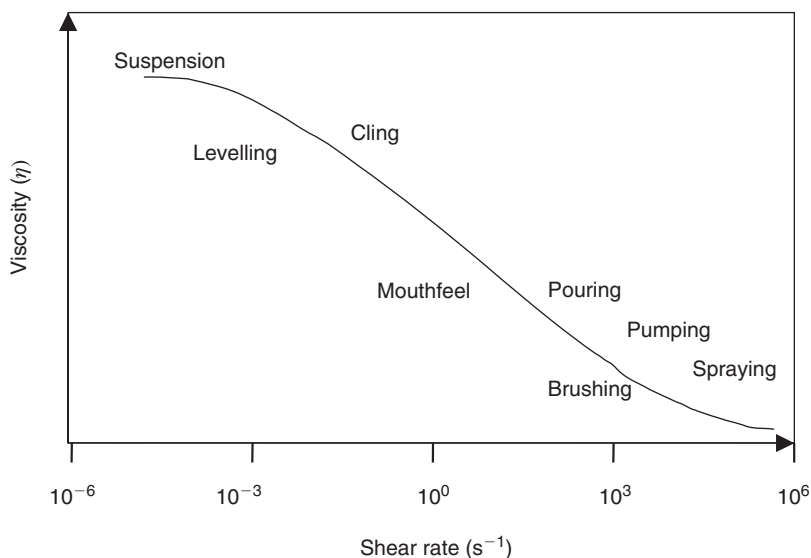




**Figure 2.9** Frequency dependence of storage modulus  $G'$  (---), loss modulus  $G''$  (—) and complex viscosity  $\eta^*$  (—) for aqueous polysaccharide systems. Mechanical spectra of (a) dilute solution ( $C < C^*$ ), (b) entanglement network ( $C > C^*$ ), (c) weak gel and (d) strong gel.

strain dependence. Furthermore, in steady shear a strong gel will rupture completely whereas a weak gel will flow, albeit without obeying the Cox–Merz superposition principal. In this case the complex viscosity ( $\eta^*$ ) is higher than the flow viscosity ( $\eta$ ). This indicates the presence of weak interactions between the molecules that contribute to the viscosity measured by the non-destructive oscillatory technique but not to the viscosity measured by the destructive flow technique.

Before discussing specific applications it is worth noting the practical significance of the flow behaviour of natural thickeners. Figure 2.10 shows the idealised flow curve of a thickener when measured over a very broad shear rate range and superimposed on this are some typical



**Figure 2.10** Idealised flow curve for an entanglement network solution and typical shear rates associated with applications of thickeners.

processes. Exact shear rates for these processes will vary depending on the particular application. The choice of thickening agent will depend on the application and the particular viscosity/shear rate profile appropriate to the process and final product. Figure 2.5 shows the flow curves of a number of hydrocolloids at various concentrations and serves to illustrate that through careful choice of the hydrocolloid and concentration the flow behaviour can be tailored to suit specific needs in terms of processing and sensory properties. To achieve the desired properties factors such as stability during the processing and shelf life of the product and compatibility with other ingredients in the formulation must be considered. In addition, the cost in use is also an important factor in the choice of thickener.

## 2.4 Dispersion and hydration

Dispersion and hydration are the first steps in all applications of hydrocolloid thickeners. To achieve the optimum functionality of any hydrocolloid, it is important to ensure the product is properly hydrated before use. The main factors that affect the hydration of hydrocolloids are dispersion, mixing speed, particle size and the composition of the solvent. As mixing speed is increased the hydration time is reduced. Particle size will have an influence on both dispersion and hydration. As the particle size increases the hydrocolloid becomes easier to disperse but slower to hydrate. In poor solvents the gum will be easier to disperse but slower to hydrate. Generally, high ionic strength or high solids slow down hydration.

For the hydrocolloid to hydrate efficiently the individual gum particles must be well dispersed in the solvent. Poor dispersion leads to lumping of particles during mixing, which results in the formation of swollen lumps (sometimes referred to as ‘fish eyes’). Severe lumping prevents complete hydration and reduces functionality. Generally, the larger the particle

size the easier the powder will be to disperse. Hydrocolloids such as LBG that are not fully soluble at room temperature disperse without problem. Dispersion can also be improved by pre-blending with other ingredients such as sugar, salts, starch, oils or alcohol.

Today many hydrocolloid suppliers offer a range of products designed for specific dispersion and hydration needs. The type of properties required will depend on the process and application. For example, in poor mixing conditions, products with larger particle size are preferred for easier dispersion. In dry mix applications such as beverages or desserts where rapid hydration is required, products with a smaller particle size are preferred. In these applications dispersion is not normally a problem due to the presence of other ingredients such as sugar, salt or proteins, which act as dispersing agents.

## **2.5 Food applications of natural thickeners**

It can be seen in Tables 2.2–2.4 that the applications of natural thickening agents are many and varied, and space does not permit to cover all of these in detail. However, the main food applications including dressings and sauces, beverages, baking and ice cream, and the main non-food applications including personal care, paper, textile printing, oil drilling and household cleaners will be discussed.

### **2.5.1 Dressings and sauces**

The key factors that influence the selection of the hydrocolloid thickener for this type of application are its stability in relation to the product formulation and process and the stability and rheology of the final product. Dressings for example are usually manufactured with a cold make-up process. They often have high levels of salt and acid, which influence the hydration and stability of the hydrocolloid. Stability in the final product in terms of oil emulsions and suspension of herbs and spices is critical. The flow properties are also important and the pseudoplastic behaviour of hydrocolloids is ideal. This provides suspension and stability due to high viscosity at low shear rates but the product remains pourable at higher shear rates. Sauces are usually prepared with a hot process and consideration of the heat stability of the hydrocolloid is important.

Xanthan gum is one of the most widely used hydrocolloids for these types of applications because of its highly pseudoplastic flow and general stability to temperature, low pH and salty conditions. It is often combined with other hydrocolloids such as starch, guar gum and propylene glycol alginate to provide different textures. For example, dressings made with a combination of xanthan and propylene glycol alginate are said to have shorter flow characteristics when poured from the bottle. In some cases, the hydrocolloid may be present as a processing aid to provide suspension during the process. For example, xanthan/guar gum combinations are often used in sauces to suspend particulate material during processing prior to the gelatinisation of starch, which provides the final product texture.

### **2.5.2 Beverages**

There are a wide variety of beverages available including dry mix products, fruit-based and dairy-based products. In dry mix products the hydrocolloids are often present at low

concentrations to provide some mouthfeel. In this application good dispersion and rapid hydration are the key. Pectin and CMC are widely used in fruit-based beverages to help provide stability. They help to prevent the formation of sediment during long-term storage. The concentration required will depend on the concentration of pulp in the juice. Dairy-based beverages are increasingly popular and in particular combinations of yoghurt with fruit or acid. These types of products are particularly challenging due to the instability of the milk proteins at low pH. Here products such as high ester pectin, CMC or propylene glycol alginate are used as protective colloids. These prevent the precipitation of the proteins at low pH. Once sufficient protective colloid has been added to stabilise the proteins, other thickening agents such as guar gum can be used to provide viscosity. Generally maximum stability correlates with minimum viscosity.

Gum arabic is widely used for emulsifying the flavour bases used in beverages. Its low viscosity in water allows the use of 15–20% gum arabic in a typical citrus oil emulsion concentrate. The high level of gum enables coverage of the oil droplet surface to prevent agglomeration. These flavour concentrates are then diluted approximately 1 to 5 with water to produce the final beverage.

### **2.5.3 Baking**

Hydrocolloids are used in the bakery industry to control dough rheology, or cake mix viscosity. They provide improved volume in bread and cakes, and can help to suspend fruit pieces in cake mixes, which results in a more even distribution in the cake after baking. Xanthan, guar, LBG and CMC are all used for this application. Moisture control is essential at all stages of cake production and poor control can result in lumpy batters, and uneven mixing, which results in poor structure and collapse during or after baking. Hydrocolloids can help to minimise these effects.

### **2.5.4 Ice cream**

Ice cream can be described as a frozen, aerated emulsion and as such is a complex system. Usually a number of hydrocolloids are used in combination in this application since no single product can bring all the desired attributes alone. The most commonly used hydrocolloids for ice cream are guar gum, LBG, carboxyl methyl cellulose, kappa carrageenan and alginate. It is also quite common to use pectin and xanthan. The addition of hydrocolloids helps to prevent shrinkage of the product during heat shock (temperature fluctuations), prevent wheying off of the proteins and control ice crystal growth. They also provide shape retention when the ice cream melts.

## **2.6 Non-food applications**

Many of the properties of natural thickeners that have been described for food applications are the same as those which make them ideal for non-food applications. For example, suspension of particles is important in abrasives and pesticides, stability and compatibility

with the formulation ingredients are also critical and, of course, rheological control is essential.

2.6.1 Oil drilling fluids

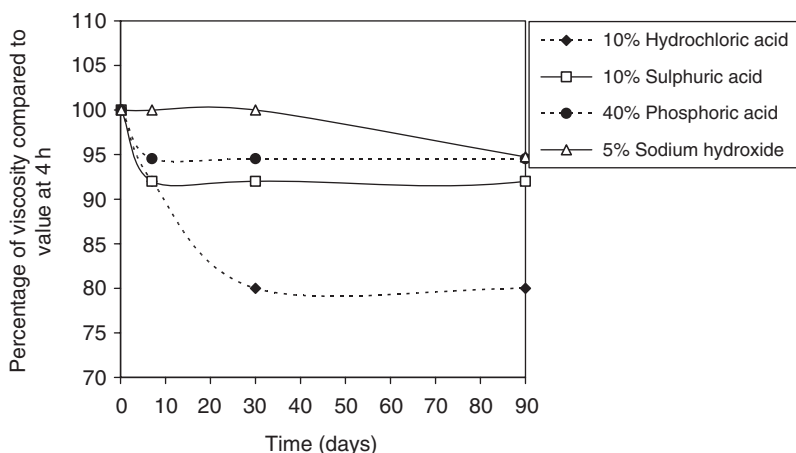
Fluids perform a range of functions in drilling. The functionality of the fluid can be directly related to the rheology of the fluid. Typically, fluids will be exposed to a wide range of shear rates from less than  $1\text{ s}^{-1}$  to more than  $100,000\text{ s}^{-1}$ . Natural thickeners, such as xanthan gum and modified guar, can ensure the correct rheology across the entire shear rate range. The fluid must have low viscosity at high shear rates as encountered at the drilling bit, and high viscosity at low shear rates as encountered in the annular region and under static conditions. The high viscosity at low shear rates helps to prevent settling of particles. The fluid must also be stable to high temperatures. CMC is also used in drilling to reduce water loss in the bore hole. The CMC is able to interact with the clay in the fluid to form a thin, dense cake at the wall of the bore hole.

2.6.2 Acidic, basic and chlorinated cleaning products

At the extremes of pH seen in this type of product very few natural thickeners are stable during the desired shelf life of the product. Xanthan gum however, shows exceptional stability in these systems and is used to provide the characteristic pseudoplastic flow properties. This enables the cleaner to be easily poured or squeezed from the container but also, through the high viscosity at low shear rates, helps the cleaner to cling to the surface and provide prolonged contact. The high pseudoplasticity also ensures the product can be easily rinsed from the cleaned surface. Table 2.6 summarises the compatibility limits for xanthan with various acid, base and chlorinated solutions, and Figure 2.11 shows that the viscosity of xanthan gum solutions remains stable over prolonged time in various acidic and basic solutions. Xanthan gum is also compatible and stable with a wide variety of detergents and wetting agents (anionic, non-ionic and amphoteric) such as sodium lauryl sulphate, ethoxylated fatty acid, ethoxylated alcohols, sodium sulphosuccinate and the sodium salts of polymeric polycarboxylic acid, mono- and di-phosphoric esters and myristyl lauryl-beta-amino propionic acid.

Table 2.6 Compatibility of xanthan with acids, bases and chlorinated solutions

Acid/base	Maximum concentration (%)
Hydrochloric acid	5.0
Sulphuric acid	10.0
Phosphoric acid	30.0
Caustic soda	5.0
Sodium carbonate	20.0
Trisodium phosphate	15.0
Sodium hypochlorite	0.5
Sodium dichloroisocyanurate	0.5



**Figure 2.11** Stability of 1% xanthan gum solution viscosity in various acidic and basic solutions (Brookfield LVT viscosity, 20°C, 60 rpm).

### 2.6.3 Personal care and cosmetics

Natural thickeners are commonly used in products such as toothpaste, shampoo and creams and lotions to control the rheology of the product. In toothpaste for example, CMC, carrageenan and xanthan are used to control the smoothness and gloss of the product. They can also improve the extrusion properties and prevent tailing when the product is squeezed from the tube. Stability is also important and natural thickeners help to maintain the ribbon on the brush and also provide stability to temperature fluctuations.

In shampoo, natural thickeners such as xanthan gum can be used as a suspending agent for active ingredients such as zinc pyrithione used in anti-dandruff formulations. Xanthan gum is a negatively charged polymer and so care has to be taken with the formulation since it is incompatible with cationic surfactants. Guar gums modified to be cationic are also used and have improved compatibility with the cationic surfactants.

The excellent water-binding capacity of natural thickeners means that product such as CMC are used as superabsorbents in nappies and female hygiene products.

### 2.6.4 Textile printing

Natural thickeners such as alginate and CMC are widely used in the formulation of textile printing pastes. They are used to control the rheology of the paste. Alginates are particularly well suited to this application due to their compatibility with fibre reactive dyes. These dyes combine chemically with the cellulosic fibres in the fabric and, unlike most natural thickeners, alginates do not react. The transfer of colour from the paste to the fabric is also good with alginate and they are easy to wash out in the finishing process.

### 2.6.5 Paper coating

Thickeners such as CMC, alginate and phosphated guar gum are used for paper coating. They improve the surface of the paper in the size press, increase strength, reduce porosity and improve resistance to grease and organic solvents.

### 2.6.6 Building materials

Natural thickeners such as CMC are used in wall paper pastes to provide a highly viscous interface between the paper fibres and the surface of the wall. CMC is also used in plaster products for binding of the gypsym particles. Thickeners such as methyl cellulose and welan are effective additives for improving the quality of building materials such as plasters and renders, mortars, tile adhesives and emulsion paints. The thickeners help to control the water balance and improve the rheological properties. For example, addition of a thickener to self-levelling floor formulations imparts pseudoplastic flow to the formulation and helps to control the settling process of the particles to provide more evenly controlled deposition of the surface. The addition of thickeners to concrete can reduce wash out in underwater construction.

## 2.7 Conclusions

It is hoped that this overview of the properties and applications of natural thickeners and their derivatives has served to illustrate the versatility of these materials. This relatively small group of products continue to present the scientists with a challenge in terms of understanding their functionality and the formulator with an opportunity in terms of innovative product development.

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## Chapter 3

# Acrylic Polymers as Rheology Modifiers for Water-Based Systems

Malcolm Hawe

### 3.1 Introduction

Many industrial processes and commercially available products only operate or function effectively through the use of carefully selected thickening agents to control the viscosity in the process or formulation. It is now recognised that a single value for the viscosity of a material does not reflect the complex behaviour of many formulations, or the wide range of conditions under which a thickener has to function across different, or even within the same, industrial process or operation.

Rheology, a term first proposed by Prof. Bingham (Lafayette College, Indiana, USA), is defined as the science that *studies the deformation and flow of matter*. When a body of material is subjected to a force that causes it to deform, the resulting behaviour of the material will be dependent on the magnitude and nature of force to which it is subjected, as well as the strength and degree of permanence of the structure or forces that exist within the material.

In order for additives to be used successfully as process or formulation aids, it is essential that their properties fully address the existing rheological limitations of the product or process, under all the conditions to which it may be exposed. In practise, this means quite simply that the system must exhibit the 'correct' viscosity, regardless of the nature, magnitude and duration of the stresses and forces to which it is exposed under 'use' conditions.

For many years, polymers, such as starches, gums and other materials derived from natural sources, were the main ingredients or additives through which the rheological properties of a system were modified and controlled. This usually meant increasing the viscosity of a mixture, for example, to improve the application properties of paint, or to provide resistance against settlement in a formulated suspension. In the past 30 years or so, rapid progress has been made in the ability of synthetic polymer chemists to manipulate and control the architecture of organic polymers. Today, industrial users and formulation chemists have access to a wide range of materials of varying chemical types, physical forms and end-use properties which, in many cases, are able to match or improve upon the properties of thickening agents available from natural or renewable sources.

This chapter considers the chemistry of the main types of synthetic polymeric thickeners used in industry as process and formulation aids. Typical manufacturing techniques used in the production of different chemical types and physical forms are considered. This chapter then looks at how polymers can be 'engineered' to produce a wide range of differing rheological profiles through the use of functional ingredients in the recipe, as well as manufacturing process conditions. Finally a number of end-use applications that use substantial

quantities of rheology modifiers will be considered. This will highlight the main features required of products in order to meet the demanding requirements of industrial processes or formulations, some of which are commercially available directly to the consumer.

## 3.2 Chemistry of acrylic polymer thickeners

Synthetic polymers can be produced by either addition or condensation polymerisation processes. Both these routes use small structural units (monomers) as building blocks that are joined together to form larger molecular assemblies, usually chain-like in nature. A wide range of raw materials is shown in the literature as being suitable for these reaction types. Nowadays, the vast majority of the polymers sold as thickening agents are addition polymers based on a handful of key building block monomers such as acrylic acid, acrylamide and acrylic ester derivatives. This situation has arisen due to several factors.

Firstly, these raw materials are available on a global basis from a number of suppliers with a price structure that makes products based on this raw material platform highly cost effective against products based on alternative chemistry. (The same monomers form the basis of product lines such as dispersing agents, flocculants and super-absorbents. A handful of global manufacturers of the latter group of products produce a total volume approaching 2 million tonnes per annum on an active polymer basis [1].)

Also, the products can be produced with varying ionic charge type and charge density to suit the compatibility requirements of a wide range of end uses.

Importantly, the products can be produced in several different physical forms such as solids (in various powder forms), oil-based liquids (where the polymer component is present as a suspension in a continuous hydrocarbon phase) and oil-in-water emulsions (where the polymer is present as the dispersed phase in a continuous phase of water). This gives the end user a significant number of permutations to choose from, depending on the priorities of price, convenience of use and suitability for the end application.

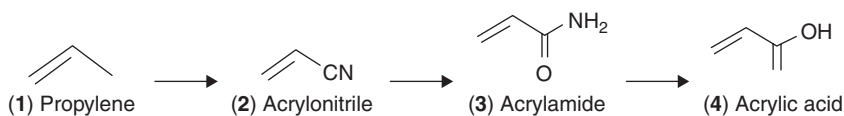
Perhaps most important of all, polymer chemists now understand in great detail how to use functional ingredients such as cross-linking agents and other specialised monomers to manipulate the 'polymer architecture' in order to satisfy virtually all the needs of a very wide range of end-use environments.

### 3.2.1 Addition polymers

#### 3.2.1.1 Monomers/raw materials

The common feature of monomers used in addition polymerisation processes is the presence of a vinyl double bond. Propylene, which is derived from crude oil, is the primary feedstock for these systems since, in addition to the carbon atoms that form the polymerisable group, the third carbon atom can be used as a source for further functionality. The route from propylene to acrylamide and acrylic acid is shown in (1–4), Scheme 3.1.

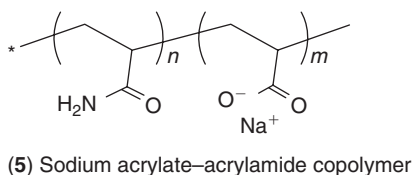
Acrylamide is described as a non-ionic monomer as it does not contain any ionisable group. However, there is sufficient polar character within the amide group to confer good solubility in water for the monomer and in homopolymers produced from this monomer.



Scheme 3.1

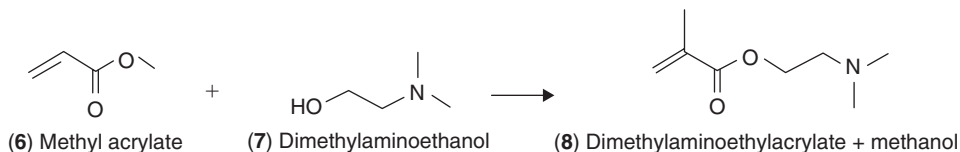
Detailed information concerning the manufacturing methods and process conditions for the key acrylic monomers is widely available [2, 3].

Acrylic acid is classified as an anionic monomer and is very soluble in water both as the acid and when part or fully neutralised with sodium, ammonium, potassium or other monovalent cation hydroxides. Acrylamide and acrylic acid can be used in mixtures at any proportion. This allows the preparation of copolymers in which the 'ionic content' or 'charge density' has been chosen by the ratio of acrylamide to acrylic acid. All products of this type are referred to generically as anionic polymers even if the carboxylic acid content is low (see (5)).



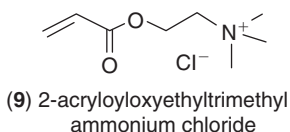
$n$  and  $m$  can each vary between 0 and 1 given that  $n + m = 1$ .

Monomers containing cationic groups are usually produced by a trans-esterification process in which a short chain alkyl acrylate is reacted with an alcohol containing a diamine group (see (6–8), Scheme 3.2).



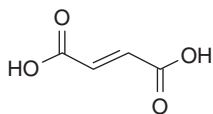
Scheme 3.2

Further reaction of dimethylaminoacrylate with a quaternising agent such as methyl chloride produces the quaternary ammonium salt shown in (9).

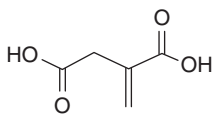


Such a monomer, and variants based on minor chemical group modifications, can be homo-polymerised or mixed with a second monomer such as acrylamide to produce cationic copolymers with a charge density determined by the chosen ratio of monomers.

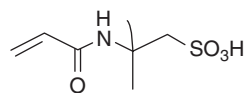
Many other acrylic, allylic and vinyl monomers are commercially available (see (10–16)) and appear frequently in the patent literature on polymeric thickening agents. In the anionic group of monomers are materials such as



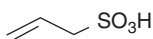
(10) Maleic acid



(11) Itaconic acid

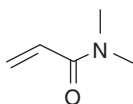


(12) 2-acrylamido-2-methylpropanesulfonic acid

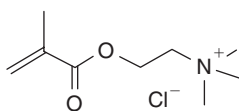


(13) Allyl sulphonic acid

Non-ionic variants tend to be less common, as the solubility in water of alkyl derivatives of acrylamide decreases rapidly with increasing chain length of alkyl substituent(s). *N,N*-dimethyl acrylamide is one example of a substituted acrylamide which has been noted as a useful co-monomer in some industrial applications.

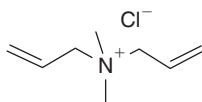
(14) *N,N*-dimethyl acrylamide

Cationic monomers include the quaternised form of the methacrylic acid ester of dimethylamino ethanol as well as a cationic derivative of acrylamide.



(15) 3-(meth)acrylamidopropyltrimethylammonium chloride

Also known is the allyl monomer.

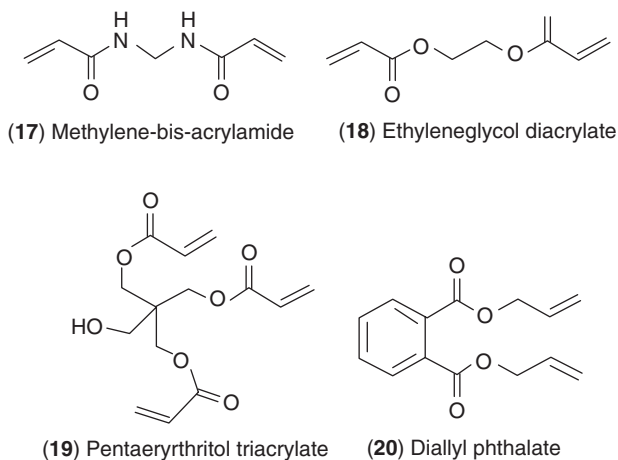


(16) Diallyldimethylammonium chloride (DADMAC)

However, many of the monomers in the latter groups are not widely used due to the problems of achieving polymer chain lengths that provide useful thickening effects. Occasionally, some of these species may have utility as co-monomers with the more common types

described earlier to provide enhanced performance in extreme or other specialised end-use environments. A second limitation to the use of these monomers can be availability and cost relative to acrylamide, acrylic acid and quaternary cationic esters.

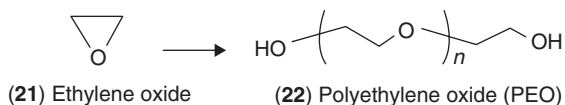
Finally, an additional group of monomers exist which are vital in providing the means by which the thickening behaviour of synthetic polymers can be modified or optimised towards the requirements in the end use. These are species that contain two or more polymerisable groups that can be incorporated into different growing polymer chains during the polymerisation reaction. Many such materials are known but commonly used examples (17–20) are shown below.



The critical effect of incorporating such monomers into the monomer recipe or polymerisation process is that the resulting polymer chains that are formed no longer have independent freedom of movement when hydrated in aqueous systems. The covalent bonds present in these molecules between the two or more polymerisable groups provide a permanent bridge, or ‘cross-links’, between neighbouring polymer chains resulting in a three-dimensional (3D) network that is essentially a permanent structure. This is one of the key features through which the thickening behaviour of polymers can be modified and controlled and will be covered in more detail later in this chapter.

Other chemical types of addition polymers are known such as polyethylene oxide (PEO), polyvinyl pyrrolidone (PVP) and polyvinyl alcohol (PVOH) (see (21–25), Schemes 3.3 and 3.4).

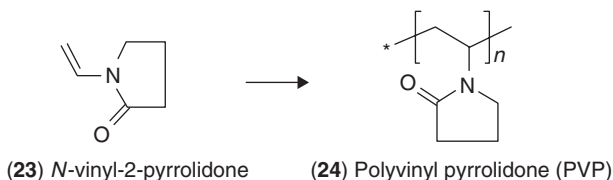
### 3.2.1.2 Polyethylene oxide (21 and 22)



Scheme 3.3

It is common for low molecular weight polymers of ethylene oxide (e.g. less than 50,000 MW) to be referred to as a polyethylene glycol. Up to this molecular weight they are not generally recognised as being useful thickeners. Although chemically identical, above 100,000 MW the term PEO is used. Some grades are available with molecular weight values of several million making them candidates for use as thickeners, especially if used in combination with other chemical types. Being non-ionic, PEOs have good compatibility with a wide range of other ingredients. This confers particular versatility when used in formulations such as personal care and household products, as well as adhesives and cement formulations in the building industry. Some degree of dual functionality is often exhibited as well, in that PEOs are noted for emollient and humectant effects, exploited in cosmetic and toiletry products (Scheme 3.4).

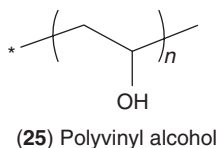
### 3.2.1.3 Polyvinyl pyrrolidone (**23** and **24**)



Scheme 3.4

Products are available at different molecular weight values and, as well as good compatibility due to the non-ionic character of the polymer, PVP has useful properties due to the solubility of this polymer in a wide range of organic solvents such as alcohols, acids and amines as well as water. It is not used routinely as a sole thickener, but approval for use in some pharmaceutical applications, such as a binding agent for tablets, provides useful opportunities for this polymer chemistry.

### 3.2.1.4 Polyvinyl alcohol (**25**)



Unlike the other addition polymers described here, PVOH is not prepared from its corresponding monomer, since vinyl alcohol does not exist as a monomer due to tautomerisation to acetaldehyde. However, the polymer can be produced by polymerisation of vinyl acetate followed by partial (85–90%) to complete (>97%) hydrolysis of the acetate groups. In both these cases the product is completely water soluble, although the use of PVOH as a primary thickener is rather limited due to the relatively low molecular weight which is obtained in the preparation of the corresponding polyvinyl acetate. Hydrophilic gels can be obtained when solutions of PVOH are mixed with sodium tetraborate.

### 3.3 Polymer synthesis techniques

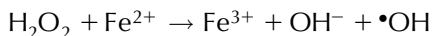
The commercial attractiveness of synthetic acrylic polymers is enhanced due to the fact that a given chemistry or composition is often available in several different physical forms. Much of the manufacturing process technology involved in the production of acrylic thickeners has close similarity with the methods used in the production of flocculants. This is also covered in Chapter 6. Specific aspects of the manufacturing process for each physical form will be considered here in the context of the use of such polymers as thickening agents.

Acrylic monomers are known to readily polymerise and will do so in an uncontrolled manner if an unintentional introduction of trace quantities of species which cause 'initiation' is allowed to happen. In order to prevent such events, and the related risks and hazards, it is usual for aqueous monomer solutions to be stabilised against spontaneous polymerisation through the use of an 'inhibitor'. Compounds such as paramethoxyphenol (PMP) are widely used in this regard, since they work most effectively in the presence of a small amount of dissolved oxygen which is usually present in water.

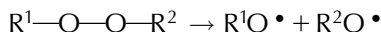
Prior to polymerisation, it is common practise to 'purge' the monomer solution with an inert gas such as nitrogen, to remove such dissolved oxygen. Alternatively, this can be achieved by applying a vacuum to the vessel containing the monomer solution and releasing the vacuum with nitrogen. The removal of dissolved oxygen reduces the effectiveness of the 'inhibitor' so that polymerisation can then be carried out in a controlled and predictable manner. Polymerisation can be induced using several different 'initiator' systems. Redox pairs involving transition metals with variable valency, such as iron and copper salts, are widely used along with compounds such as peroxides. Other initiators are known which readily decompose at known rates at defined temperatures. Compounds such as 2,2'-azobis(2,4-dimethylvaleronitrile), 2,2'-azobis(2-amidinopropane)dihydrochloride and 2,2'-azobisisobutyronitrile, along with others based on organic peroxides such as tert-butyl hydroperoxide, 2,5-dimethyl-2,5-di-(hydroperoxy) hexane, cumene hydroperoxide and tert-butyl peroxyphthalate are well known and widely used as thermal initiators.

Whichever initiator type is used, the purpose is to generate free radicals that can then react with the polymerisable group in the monomer to initiate the polymerisation reaction.

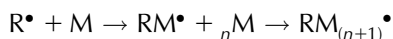
A typical redox reaction would be:



A typical thermal decomposition would be:



Polymerisation then takes place through sequential addition of further monomer units:



Chain transfer reagents such as mercaptans and lower alcohols may be employed to stop further reaction of monomer units into a growing polymer chain. Such species then act to transfer the free radical to become the initiator for the start of growth of another polymer chain. Polymerisation is essentially complete when radicals are no longer being generated and

all the monomer has been consumed. The remaining radical species within the polymer chain network are eliminated through combination or disproportionation reactions.

### **3.3.1 Polymer physical forms**

#### *3.3.1.1 Solid grades: gel polymerisation process*

This manufacturing method involves preparing a solution of the required monomer or mixture of monomers in water at a defined concentration. Anionic, non-ionic and cationic polymers of varying copolymer composition are widely available in this form. The monomer concentration used is influenced by the calculated reaction exotherm of the monomer mixture, the temperature at which polymerisation is initiated, the heat capacity of the continuous phase (usually water) and any heat losses or deliberate cooling effects applied during the course of the reaction. At the end of the polymerisation process, the water thin solution of monomer has been converted to a tough gel resembling rubber in consistency. In order that the product can be supplied to the end user in an easy to handle and cost effective manner, it is common practise to remove the water from the polymer gel. This is achieved more easily if the gel is cut or processed into small particles before being subjected to dehydration, often using a fluid bed drier. This batch-based process has been carried out on an industrial scale for over 30 years and is often favoured for achieving the highest molecular weight grades in anionic, non-ionic and cationic chemical types. In recent developments, some continuous processes are being operated, where polymerisation takes place on a moving belt or in a vertical column.

#### *3.3.1.2 Solid grades: suspension of bead polymerisation process*

This process involves adding an aqueous monomer solution under controlled stirring conditions into a vessel containing a low viscosity hydrocarbon liquid. The immiscibility of the two phases causes the aqueous phase to break up into droplets, typically around several hundred microns in diameter. Redox or thermal initiators are used to effect polymerisation and at the end of the process, the water remaining in the polymer particle is removed by distillation under vacuum. The final product is then a spherical free flowing bead and can be of any of the chemical types. The highest molecular weight grades are more difficult to achieve by this manufacturing process.

#### *3.3.1.3 Solid grades: precipitation polymerisation process*

This process exploits an unusual effect of the difference in solubility of acrylic acid monomer and polyacrylic acid in specific solvents. When products based on the process were first developed [4] and made commercially available, benzene was used as the polymerisation medium. The polymerisation reaction is initiated in a system containing a mixture of acrylic acid monomer and a cross-linking monomer (typically a multi-allyl ether derivative of sucrose or pentaerythritol) and, as the polymer network grows, the solubility in the solvent decreases until precipitation of the polymer network occurs in the form of a small particle size powder. The use of a cross-linking monomer results in a 3D network of



polymer chains throughout each particle. The product is recovered as a fine powder which can be used to thicken aqueous systems. Partial or complete neutralisation of the acid group, usually with a monovalent cation hydroxide, results in a dramatic expansion of the network due to the effect of charge repulsion between neighbouring ionised carboxylic acid groups. The excellent efficiency and sparkling clarity of aqueous systems thickened with such polymers make them particularly interesting for use in cosmetic and toiletry products. Many countries require the ingredients used in personal care formulations to be listed on the product packaging sold to the consumer. The industry has developed a naming convention known as the INCI list (from the International Nomenclature of Cosmetic Ingredients) that is used for all raw materials. Each supplier has a sales or trade name for their own product range, but for labelling/packaging purposes, the INCI name is used on the list of ingredients. Carbomer is the INCI name in use for the type of cross-linked acrylic acid polymers described here.

Certain limitations in the use of this product type resulted in extensions to the product range available from certain suppliers. In the early 1990s a new range of Carbomer polymers was introduced [5]. The products are manufactured using an alternative solvent for polymerisation based on a mixture of ethyl acetate and cyclohexane and were introduced to address lingering safety concerns regarding the possible presence of trace amounts of benzene in the conventional Carbomer grades. Other developments [6, 7] were also made to overcome the dusty nature of Carbomer polymers that caused users some difficulty in the stage where the powder was being dispersed into water. These surfactant-modified Carbomer grades [8] are also claimed to provide improved formulating latitude and application properties.

### 3.3.2 *Liquid grades*

Liquids represent a simple and convenient physical form and various thickening agents based on acrylic polymer chemistry are available in this form. Two main routes for producing such liquids are known. Firstly, a water-in-oil polymerisation process can be used for the preparation of polymers that are directly soluble in water. Alternatively, an oil-in-water emulsion process is used where the polymer composition is chosen to be water insoluble during the preparation stage, but which can be made water soluble by a neutralisation reaction after polymerisation has been completed. More specific information on these two key processes is given in the following sections.

#### 3.3.2.1 *Inverse emulsion polymerisation process*

As described earlier in the section on bead or suspension polymers (Section 3.3.1.2), a solution of monomer(s) is prepared in water and then mixed into a low to medium viscosity non-volatile oil phase. In this process, which is often referred to as an inverse emulsion polymerisation technique, surfactants which promote the formation of water-in-oil emulsions are commonly used. These would usually be materials with an HLB (hydrophilic-lipophilic balance) value in the range 4–7, an example of which is sorbitan mono-oleate. In order to achieve the desired droplet particle size of a maximum around 1  $\mu\text{m}$  prior to polymerisation, high shear homogenisers are used to assist the formation of such very small

particles. Polymerisation is achieved using redox and or thermal initiators as described previously. In general the process is operated on a batch basis, although some loop reactor configurations are known. After polymerisation, the polymer droplet or particle, still containing the water from the initial monomer solution, remains suspended in the oil phase. The average size of approximately  $1\text{ }\mu\text{m}$  is necessary to avoid settlement of the polymer particles over time and so achieve a reasonable 'shelf life' for the product. It is also usual to add a second surfactant at this stage which is much higher in HLB value, typically 11–14. This material, variously referred to as an 'activator', 'inverter' or 'breaker' provides rapid emulsification of the continuous oil phase when the product is added to water so allowing rapid swelling and/or dissolution of the polymer particles once contact is made with water. In the so-called inverse emulsion polymers, the active polymer content can range from 25% to 45% of the product as supplied depending on the specific composition of the homo- or copolymer. In a variation on this theme, some products are available in which the water remaining in the polymer particle after polymerisation is removed by vacuum and/or azeotropic distillation. This allows the active polymer content to increase to between 45% and 60%, again dependent on the chemical composition of the polymer. Such dehydrated products are described as liquid dispersion polymers or LDPs.

This is a very versatile process for the polymer chemist, as the polymer can be any one of the three chemical types of anionic, non-ionic or cationic. The polymer molecular weight can vary from low-, through medium-, to high- and cross-linking agents can be included in the initial monomer solution, all without changing the nature of the product in the as-sold form. However, the intentional variation of any or all of these factors will have a substantial effect on the viscosity behaviour of the system when the polymer is eventually used in an aqueous system.

A further component that can be varied, to take into account the requirement or specific needs of the end-use environment, is that of the continuous phase oil. For products to be used as thickeners in general industrial operations, such as Improved Oil Recovery or Print Paste formulations for textiles, this phase is usually based on a mineral oil hydrocarbon. In products developed for more specialised or demanding end uses, such as cosmetic and toiletry formulations, special grades are available where the continuous phase is a medicinal-grade high-purity 'white' oil. Hydrophobic esters and even silicone-based fluids have also been used as the continuous oil phase.

### 3.3.2.2 *Water-based emulsion polymerisation process*

Thickening agents based on aqueous emulsion polymer chemistry were first developed [9] in the late 1950s and represent another important class of thickening agents. In this physical form, a monomer composition is chosen that provides a balance between the hydrophilic nature of a carboxylic acid monomer (such as acrylic, or more usually methacrylic acid) and a hydrophobic alkyl (meth)acrylate monomer (such as methyl methacrylate, ethyl acrylate, butyl acrylate or mixtures of such species). Whilst the carboxylic acid is in the free-acid form the overall composition is balanced to sufficiently hydrophobic to be water immiscible. This allows the monomer mixture to be reacted using a conventional oil-in-water emulsion polymerisation technique.

Typically, the liquid monomer phase is mixed with water containing an anionic emulsifier, to form droplets of monomer in water. This emulsion is then fed directly into a stirred reactor

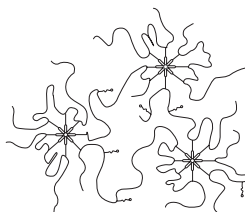
containing further water. The reaction vessel is also supplied with a solution of an initiator such as ammonium persulphate. The feed rate of the monomer emulsion can be controlled to maintain the reaction vessel at a steady temperature as the heat generated by the exothermic polymerisation balances heat loss from the vessel and/or any applied intentional cooling. After completing the addition of monomer, the reaction vessel is maintained at an elevated temperature for sufficient time to ensure all the added monomer has fully polymerised. The product of this process is a milky white, opaque to translucent, low viscosity liquid with an active polymer content around 25–40% by weight. The polymer can be made readily soluble, usually after dilution in water, by neutralisation of the carboxylic acid group with a monovalent base such as sodium hydroxide or ammonium hydroxide. The requirement for neutralisation in order to function as an effective thickener restricts the use of such materials to neutral or alkaline pH environments. Such polymers are therefore particularly suited for systems such as water-based emulsion paint formulations which are mainly in this pH range.

Polymers prepared as 'linear' or 'uncross-linked' types have molecular weights typically in the range from around  $1 \times 10^5$  to  $2 \times 10^6$  mass units. The relatively modest molecular weight values of such polymers means that significant addition levels are needed in order to generate the required degree of thickening. Conversely, a molecular weight value in this region reduces the likelihood that the thickener will induce flocculation of the other key components in emulsion paint. This tendency is further reduced since the anionic character of these polymers means they have little or no tendency to adsorb onto the dispersed pigment present in such systems, as the commonly used minerals such as kaolin, calcium carbonate and titanium dioxide are usually pre-treated with an anionic dispersing agent that confers a negative surface charge or zeta potential to the solid. The latex component is also negatively charged at the surface through the use of anionic surfactants in the preparation of the latex polymer emulsion. Consequently, the alkali-activated emulsion polymer influences the viscosity characteristics of the system wholly through its action on the continuous aqueous phase.

A substantial increase in thickening efficiency is seen when polymers of this type are prepared with a cross-linking monomer incorporated in the monomer recipe. Although improving the thickening efficiency, a corresponding change to the viscosity profile also occurs lessening the suitability of such products for water-based paints. In practise, cross-linked polymers are better suited to formulations such as tile adhesives, grouts and other mineral-based cements. The reasons for this will be covered in the section on rheological profiles (Section 3.5).

The limitations of this product group as rheology modifiers had been recognised for some time and similar limitations applied to other acrylic polymer product forms. The basic rule which applies means that thickening efficiency improves as polymer molecular weight increases but, in formulations containing particulates or some other form of dispersed phase, flocculation of this phase is often the result of adding high molecular weight polymer (an effect which is essential for some industrial uses (see Chapter 6)).

During the mid to late 1970s a significant amount of research work was undertaken in an attempt to address this deficiency. It became known that the presence of hydrophobic groups in hydrophilic polymers resulted in the hydrophobic groups interacting with one another once the host polymer was dissolved in water. A number of different ways of achieving this effect were developed and these materials, commonly referred to as 'associative polymers', increased in importance such that this product type became the subject matter



**Figure 3.1** Associative polymer solution.

of a wide number of publications [10, 11] conferences and symposia. In practise, the alkali-activated water-based acrylic emulsion polymer type has emerged as the most widely used type of synthetic associative polymer. A significant number of patents were issued covering developments in this area. One review [12] identified 19 references to hydrophobically modified alkali-activated emulsions and acknowledged that this was not necessarily a complete list of all relevant publications. A popular way of introducing a hydrophobic group is through the use of a non-ionic surfactant such as a long chain alkyl ethoxylate in which the terminal hydroxyl group is used as a reactive site for the attachment of a group containing a polymerisable double bond. The alkyl group is generally lauryl (C12) or greater, and the hydrophilic component usually based on 10 units of ethylene oxide or more. The presence of the ethoxylate chain seems to act as a useful spacer group between the hydrophobic head on the pendant side chain and the ionic polymer backbone.

A schematic representation of a solution of associative polymer is shown in Figure 3.1.

Besides improving the absolute level of thickening efficiency, the interactions of the hydrophobes in aqueous solution were also seen to affect in a beneficial manner the other properties of formulations based on such polymeric thickeners. The micellar clusters formed by the assembly of hydrophobes in the aqueous phase aggregate even more strongly when simple 'salts' are also present in solution. This arises due to the fact that the critical micelle concentration (CMC) of the surfactant forming the side chain is somewhat lower in electrolyte solutions than in water alone. This effect, which boosts viscosity, helps to offset the reduction in thickening efficiency that inorganic and other salts have on conventional polyelectrolytes.

In formulations such as household cleaners or cosmetic and toiletry products, it is common for surfactants to be present in order to provide the required detergency effect. Consequently, the water phase has an assembly of micelles in addition to those which form from the groups in the polymer. In practise, the hydrophobes in the polymer become incorporated in the surfactant micelles originating from the components of the formulation which results in association or interactions greater than that which would arise from the polymer surfactant groups alone.

Finally, the structure or network of polymer chains combined with micellar clusters occurring in solution from such associative polymers also results in a modified rheological profile with respect to the viscosity versus shear rate behaviour compared with the previously known 'linear' and 'cross-linked' types. This was of particular interest in formulations such as water-based paints and will be covered in more detail in a later section on rheological profiles of acrylic thickeners.

### 3.4 Polymer characterisation

The common anionic, non-ionic and cationic monomers can be readily polymerised to very high molecular weight, such that they routinely exceed the upper molecular limits of well-established techniques such as size exclusion chromatography (SEC). Estimates based on empirical methods such as intrinsic viscosity determination, indicate that polymer chains with 100,000 units and more can be expected during routine synthesis of such polymers. This corresponds to the polymer chain having a molecular weight around 10 million or more.

When prepared as a dilute solution in water, the polymer dissolves and forms an interpenetrating network of polymer chains which are independently mobile. This network is reflected in a substantial increase in viscosity over that of water and is responsible for the rheological properties of the polymer solutions.

#### 3.4.1 Polymer characterisation techniques

##### 3.4.1.1 Chemical analysis methods

The chemical composition, including ionic character of the component monomers, can be determined using various standard chemical and instrumental analysis procedures such as GC-pyrolysis, IR and NMR spectroscopy, as well as elemental analysis techniques.

Any understanding of the chemical composition of a polymer obtained from such methods can only indicate a small part of the information needed to describe the polymer, as this information alone does not reflect the properties that the polymer will exhibit when used as a thickener. Efficient thickening is usually the result of achieving very high molecular weight in the polymerisation process and preserving this through into the end-use environment. A number of techniques exist which are able to provide information on polymer molecular weight and molecular weight distribution. The usefulness, or otherwise, of some of these techniques will be considered in more detail as they apply to synthetic thickeners.

##### 3.4.1.2 Size exclusion chromatography (SEC)

In SEC, polymer molecules of differing chain length are separated using an elution process on a column packed with small porous beads made of a chemically inert material. During the elution process, the shorter chain molecules become trapped within the pores of the column packaging and so endure a more tortuous path and a longer residence time on the column. A measurement of polymer concentration in the eluate from the column versus time thus provides a 'profile' of the molecular weight distribution within the sample. Standards of known molecular weight are required to calibrate the column in order that elution time can be correlated with molecular weight. Such standards are only available for a limited number of polymer chemical types and PEO is typically used for water-based SEC. Consequently, any molecular weight data generated on different chemical types using PEO standards is a relative rather than an absolute measure of molecular weight.

Polyelectrolytes are renowned for their strong affinity for solid surfaces and the column packing material is no exception. Buffered electrolyte solutions are routinely used to prevent (or at least limit) these interactions as well as to suppress inter- and intra-molecular

electrostatic effects present within the polymer chains. The accuracy and precision of these types of procedures can be further enhanced through the use of additional equipment such as on-line viscometers [13] or light-scattering devices [14] which add to the information available on the material present in the eluate.

However, it should be noted that some ultra high molecular weight fully soluble grades and cross-linked polymers of any physical form or chemical type are not suited to this procedure.

### 3.4.1.3 *Light scattering methods*

Light scattering has been known as a method [15–17] of determining molecular weight and molecular weight distribution for many years. During light scattering measurements, excess Rayleigh scattering,  $R$  (the ratio of scattered to incident radiation minus the scattering from pure solvent), is measured and related to  $M_w$  (weight average molar mass) according to the light scattering equation:

$$\frac{Kc}{R_\theta} = \left[ \frac{1}{M_w p_\theta} \right] + 2A_2c \quad (1.1)$$

where  $c$  is the concentration of polymer;  $K$ , a constant (containing several terms);  $A_2$ , the second virial coefficient (related to solute/solvent interactions) and  $p$ , the angular dependence of excess Rayleigh scattering.

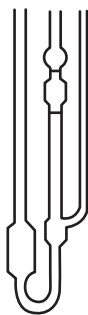
For small molecules or low molecular weight polymers,  $p$  is 1, as there is no significant angular dependence of the scattering function. Consequently,  $M_w$  can be determined at any angle. For higher molecular weight species, angular dependence is relevant and  $M_w$  needs to be measured at zero angle. In practise, measurements are made at several low-angle values and the data extrapolated to zero angle. In addition to static measurements where the polymer sample is measured in a cuvette, light scattering measurements can be used in combination with size separation techniques such as SEC [14, 18] and to other recent developments such as field flow fractionation [19, 20].

Light scattering techniques provide absolute values for molar mass and so require no other polymer standard for calibration purposes. The molecular dimension causing scattering is related to the volume of the equivalent sphere occupied by a single polymer chain when present in solution as a random coil.

Cross-linked polymers which exist in aqueous systems as micron or sub-micron-sized particles have characteristics which do not compare with those of soluble polymers. Any measurements made using light scattering techniques should not be used for comparative purposes between cross-linked and soluble polymers.

### 3.4.1.4 *Viscosity-based techniques*

Due to the highly efficient nature of these polymer types as thickeners, viscosity-based characterisation studies are usually carried out on dilute solutions, typically at a concentration of <1% polymer in water. Despite the non-Newtonian behaviour of these solutions (which is covered in more detail later in this chapter) useful information reflecting the character of the polymer present in solution can be obtained using cheap, simple and reliable equipment such as glass U-tube viscometers.



**Figure 3.2** Suspended level viscometer.

Various types are known such as Ostwald, Cannon–Fenske and Ubbelohde (also referred to as a suspended level viscometer or SLV) as shown in Figure 3.2.

Such viscometers are available with varying capillary tube diameters. This allows a wide range of viscosity values to be measured at flow times suited to routine laboratory work. In practise, this type of equipment is only used for simple characterisation techniques such as quality control checks, and usually only when a ‘fit for purpose’ polymer has been characterised and standard conditions defined in order to provide a benchmark or reference result against which other samples can be compared.

### 3.4.1.5 Intrinsic viscosity

One method which is a variation on this theme and which provides useful data on polymer characteristics is the determination of an intrinsic viscosity value. Glass capillary viscometers (see Figure 3.2) are widely used for such measurements. This exercise involves measuring the viscosity of the polymer in solution at one or more concentrations and comparing this with the result for the solvent alone. A number of terms have been defined for such studies as follows:

- Relative viscosity ( $\eta_{\text{rel}}$ ) is the ratio of the viscosity of the polymer solution ( $\eta$ ) to the viscosity of the pure solvent ( $\eta_0$ ), that is:

$$\eta_{\text{rel}} = \eta/\eta_0 \quad (3.2)$$

In practise, this is also the ratio of the flow time of the polymer solution ( $t$ ) to the flow time of the solvent ( $t_0$ ) as the viscometer constant is the same in both cases, that is:

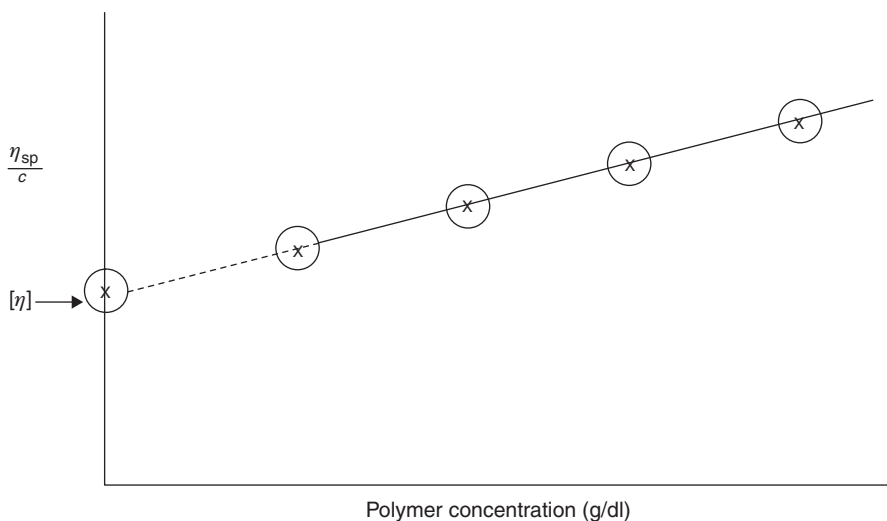
$$\eta_{\text{rel}} = t/t_0 \quad (3.3)$$

- Specific viscosity ( $\eta_{\text{sp}}$ ) is defined as:

$$\eta_{\text{sp}} = (\eta - \eta_0)/\eta_0 \quad \text{or} \quad \eta_{\text{rel}} - 1 \quad (3.4)$$

- Reduced viscosity value is defined as:

$$\eta_{\text{red}} = \frac{\eta_{\text{sp}}}{c} \quad \text{or} \quad \frac{(\eta_{\text{rel}} - 1)}{c} \quad (3.5)$$



**Figure 3.3** Graph 1: Intrinsic viscosity.

Relative viscosity and specific viscosity are dimensionless, but reduced viscosity has units of the reciprocal of concentration, or dl/g. The value of reduced viscosity varies with polymer concentration. Measurements can be made at several concentrations (usually four) and then presented graphically (see Figure 3.3).

Extrapolation to the intercept on the  $y$ -axis gives the reduced viscosity value at zero concentration. This is the limiting viscosity number, more widely referred to as the intrinsic viscosity. This value also has units of reciprocal concentration (dl/g). This can be regarded as the volume occupied in solution by 1 g of polymer at infinite dilution. Under such conditions the polymer chain can be considered as having complete freedom to adopt a random coil configuration dictated solely by the number of units making up the polymer chain; that is to say, the configuration adopted by each polymer molecule is independent and free from the influence and constraints of neighbouring polymer chains. For polyelectrolytes, it is common for intrinsic viscosity determinations to be carried out in a buffered electrolyte solution of sufficient ionic strength to suppress inter- and intra-molecular electrostatic effects which would otherwise influence the spatial configuration of the polymer chain.

The intrinsic viscosity value determined in this way can be related to the molecular weight of the polymer through the Mark–Houwink equation:

$$[\eta] = KM_v^\alpha$$

where  $K$  and  $\alpha$  are constants, and  $M_v$  is the viscosity-based average molecular weight of the polymer. Values of  $K$  and  $\alpha$  are available [21] for a large number of polymers and solvents, although the information on these constants is rather limited for acrylic copolymers in aqueous systems. The calculation of molecular weight values in this way is not a necessity as intrinsic viscosity values are equally useful for comparative purposes, provided the comparisons are being made between materials of the same composition.

Whilst measurements can also be carried out with cross-linked polymers, (provided the primary particle size is sufficiently small to avoid blockage of capillary section of the U-tube



**Table 3.1** Influence of cross-linker level on intrinsic viscosity

Sample	Cross-linking agent (ppm)	Intrinsic viscosity (dl/g)
Polymer A	0	12.9
Polymer B	40	13.1
Polymer C	80	9.3
Polymer D	120	7.9
Polymer E	250	5.3

viscometer!), caution should be exercised in the interpretation of any such results. The 'apparent' intrinsic viscosity values of cross-linked polymers cannot be meaningfully compared with those for fully soluble polymers, as the presence of cross-linking agent substantially restricts the freedom of movement of the polymer chains present in the 3D network which forms such particles. The apparent volume occupied by the polymeric species at zero concentration/infinite dilution is more a reflection of the degree or level of cross-linking.

This was shown to good effect in an experiment [22] carried out to prepare a series of cationic acrylamide copolymers (60/40 weight ratio) as inverse emulsion polymers using identical polymerisation conditions, in which only the concentration of cross-linking monomer was varied. Subsequent determination of intrinsic viscosity values for this set of polymers showed the results in Table 3.1.

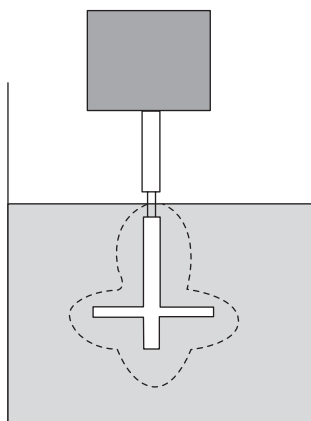
The reduction in intrinsic viscosity observed as the level of cross-linking agent is increased does not reflect a smaller number of units in each chain (i.e. a polymer of lower molecular weight) but the effect of the cross-linking agent generating covalent bonds between neighbouring polymer chains, preventing chain disentanglement and separation during dilution.

The measurement of intrinsic viscosity using capillary viscometers can be a labour intensive and time-consuming exercise. However, polymer chemists undertaking characterisation studies in this way have been spared a significant amount practical work as a result of the development of so-called 'single point equations'. These provide a method by which intrinsic viscosity can be determined when the flow time for the polymer solution is determined at only one concentration and compared to the flow time for that of the solvent alone. Solomon and Ciuta [23] proposed the following equation for use:

$$[\eta] = \frac{1}{c} \left[ 2(\eta_{sp} - \ln \eta_{rel}) \right]^{1/2} \quad (3.7)$$

One review [24] considers the theoretical derivation of several such equations, and highlights the effect of polymer concentration and the nature of the solvent in the correlation of intrinsic viscosity values calculated using such equations compared with extrapolated value for  $[\eta]$ . In summary it should be recognised that:

- Capillary viscometers, whilst best suited to the measurement of Newtonian fluids, can be used to provide some very useful information which is an accurate representation of the nature of the polymeric species when these are present as true solutions.
- Meaningful comparisons of intrinsic viscosity results can only be made if the polymers being studied are of the same general composition and type.



**Figure 3.4** Rotating spindle.

- Intrinsic viscosity values for cross-linked polymers do not provide results that correspond to the number of units present in the polymer chain; the low values for intrinsic viscosity obtained when measuring such materials reflect the constraints to expansion of the 3D polymer network during dilution (and possibly an unknown contribution from a small proportion of soluble polymer).

### 3.4.2 Rotational viscometers

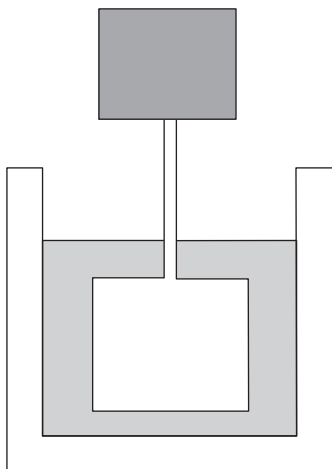
Rotational viscometers have been used as alternatives to capillary viscometers for many years. The basic instruments are relatively cheap, robust and simple to operate, easy to clean and give results in a short period of time. Such viscometers are commonly used with the simple spindle/disc type measuring geometries which well suit the characteristics of Newtonian fluids. Concerns arise using this sort of measuring system for non-Newtonian fluids and two main issues are the source of these problems. Firstly, when immersed in the fluid, the rotation of the spindle/disc generates forces throughout an ill-defined volume of the fluid. Secondly, the angular velocity of the rotating disc varies from close to zero at the axis to a maximum at the outer edge of the disc and the force imparted to the fluid varies with the effective rotational velocity.

A spindle/disc measuring geometry in an 'infinite sea' of liquid.

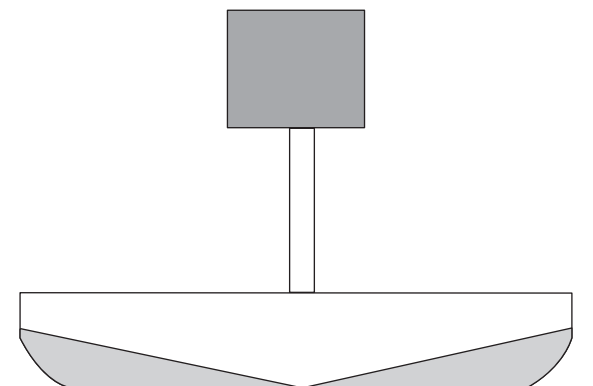
Consequently, different regions of the sample are exposed to widely different shear force conditions and the viscosity value obtained when carrying out such a measurement is the net result of all these different un-quantified effects.

More advanced measuring geometries are available to ensure that the shear rate to which the sample is exposed during measurement is uniform and, of equal or greater importance, is a value that can be quantified. Two alternative measuring geometries now widely used are shown schematically in Figures 3.4 and 3.5.

A number of variations on the cylinder geometry are known such as those with a conical base. Others may have a recessed base (Figure 3.6). These alternatives attempt to address the



**Figure 3.5** Coaxial cylinder (couette) geometry.



**Figure 3.6** Cone and plate geometry.

variable shear rate conditions which exist in the fluid below the rotating cylinder as noted earlier for the spindle/disc geometry.

This geometry compensates the increase in angular velocity across the radius of the cone by a corresponding increase in the volume of fluid according to the cone angle. This ensures a constant shear rate is applied to the sample across the radius of the cone.

The importance of having information of the shear rate at which the measured viscosity value was determined is very important, as is the ability to generate shear rate conditions during measurement which reflect those in the end use. Without this, the identification and selection of the best product for a given end use is made more difficult. Table 3.2 shows the typical shear rate range that is generally accepted as being present in various applications or end-use environments where polymeric thickeners might be used.

**Table 3.2** Typical shear rate values in industrial end uses

Environment	Typical shear rate range ( $\text{s}^{-1}$ )	Examples of end uses
Suspension of fine particles in a liquid	$10^{-6}$ – $10^{-3}$	Cosmetic formulations, emulsion paints
Levelling and flow on a surface	$10^{-2}$ – $10^{-1}$	Printing inks, emulsion paints
Vertical flow under gravity	$10^{-1}$ – $10^1$	Emulsion paints, toilet cleaners and bleaches
Mixing and stirring	$10^1$ – $10^3$	Preparation of formulations
Flow in a pipe	$10^0$ – $10^3$	Hydraulic transport, sewer flow
Brushing	$10^3$ – $10^4$	Painting
Rubbing	$10^4$ – $10^5$	Application of skin/hair care creams and lotions
High-speed machine coating	$10^4$ – $10^7$	Blade application of paper coating colour
Spraying	$10^5$ – $10^6$	Aerosol atomisation

### 3.5 Basic concepts of rheological behaviour

It is beyond the scope of this chapter to consider in detail the many issues related to the theoretical and practical aspects of the non-Newtonian behaviour of polymer solutions. A large amount of published literature is available for readers requiring more detailed information ranging from the introductory to the advanced level [25–28]. One author [29] includes a chapter listing a comprehensive library of books on *rheology*, categorised into both theoretical and practical aspects of the science.

However, it is worthwhile considering some of the underlying principles on which the science and measurement of rheology is based, in order to understand how the different polymer types discussed in this chapter behave in end-use environments.

Consider a cube of material (shown in solid lines in Figure 3.7) made up of an infinite series of layers. When a force,  $F$ , is applied to the uppermost layer (of area,  $A$ ) a displacement occurs, shown by broken lines.

The outcome of applying this force to the cube can be described by two extremes.

- Newton's law for viscous fluids: In 'Principia' Isaac Newton noted that '*The resistance which arises from the lack of slipperiness of the parts of the liquid, other things being equal, is proportional to the velocity with which the parts of the liquid are separated from one another.*' Today, we recognise this as the magnitude of the viscosity of the system. In other words, the internal friction which exists between the layers creates a resistance to movement against the applied force. For simple Newtonian fluids, resultant velocity is directly proportional to the applied force and flow continues for as long as the force is applied. Each layer moves at a slightly different rate to its neighbour in proportion to the internal friction or viscosity.

This can be represented in the following equation:

$$F/A = \eta V/X$$

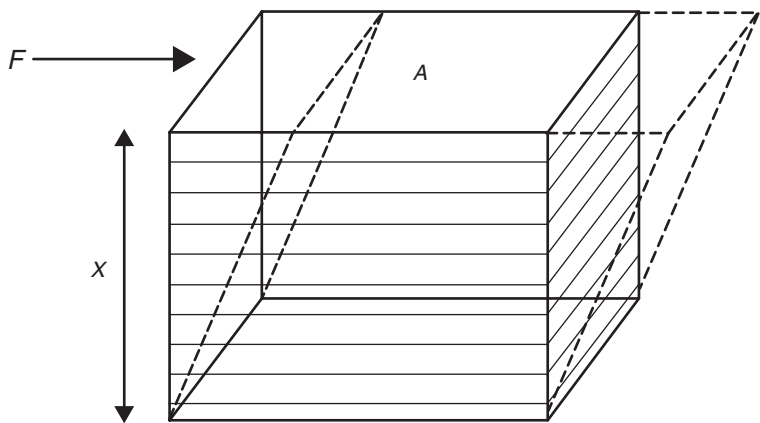


Figure 3.7 Shear force cube.

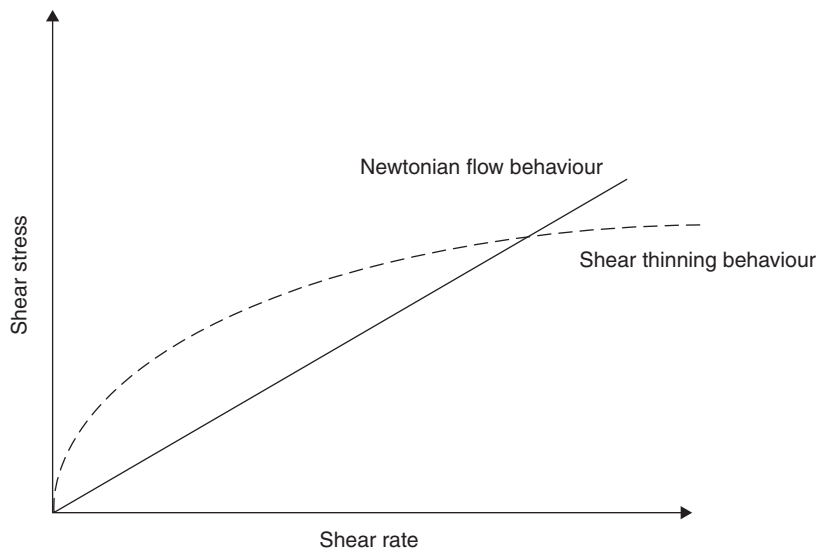


Figure 3.8 Graph 2: Shear stress versus shear rate profile.

where  $F$  is the force acting on area  $A$  and  $F/A$  is the shear stress, referred to by the symbol  $\sigma$  (sigma). And  $V/X$  is the velocity gradient or shear rate, referred to by the symbol  $\dot{\gamma}$  (gamma dot),  $\eta$  is the coefficient of viscosity (and equals shear stress divided by shear rate). A plot of shear stress against shear rate then shows a straight line relationship (see Figure 3.8) non-Newtonian systems, by definition, show a nonlinear relationship between shear stress and shear rate and polymeric systems discussed here are almost exclusively shear thinning (a typical profile is shown in Figure 3.8).

- Hooke’s law for elastic solids: Also back in the 17th century, Robert Hooke developed his ‘True Theory of Elasticity’. In this he proposed that ‘the power of any spring is in the same

*proportion with the tension thereof*. In practise, this means the increase in extension is directly proportional to the tension exerted. In the context of the cube shown in Figure 3.6, an applied force  $F$  acting on a perfectly elastic system would result in an instantaneous deformation of the cube in proportion to the force applied. No further movement of the material occurs, and when the force is removed the material recovers to its original state.

In practise, aqueous systems containing synthetic polymers of this type exhibit complex behaviour that shows elements of both these effects. Consequently, the term viscoelastic is commonly used when referring to such systems. These effects arise in the entangled mass of chains present in a true solution of polymer, as well as in the interlinked polymer chain network present within the water swollen micro-particles of 'cross-linked' polymers.

### 3.5.1 Advances in rheological characterisation

For many years, rotational viscometers made measurements of viscosity by operating at known speeds with the resultant behaviour of the sample being detected through the measuring geometry. The Weissenberg Rheogoniometer, probably the first instrument to fulfil the needs of research work in this area, was able to cover shear rates between  $\sim 10^{-4}$ /s and  $10^4$ /s, although generating data could be a time-consuming task.

Controlled speed instruments are not well suited to measuring the properties of samples possessing weak or fragile structures but during the 1970s, controlled stress instruments became commercially available mainly as a consequence of advances in air-bearing and air-turbine technology. Probably the best known of these is the Deer Rheometer. Further advances, particularly in optical-disc technology, improved dramatically the sensitivity for detecting the rate of rotation (some of the latest instruments can detect rotation rates equivalent to one revolution in 20 years). Similar improvements have also been achieved in the magnitude and accuracy of the minimum torque values that can be applied to a sample. Coupling these advances with sophisticated data capture and high-speed data processing available on desktop computers, allows substantial amounts of information to be gathered quickly and easily. Today, these instruments are controlled by bespoke software which can be programmed to carry out one or more characterisation techniques in sequence. The results can be presented in tabular and/or graphical form with a wide choice of variables available for both the  $x$ - and  $y$ -axes. This provides the polymer chemist, rheology scientist and formulation chemist a wealth of information to manipulate and optimise polymeric thickeners such that they meet the end-use needs in the best possible way.

Several different characterisation methods are used routinely. These will now be considered in the context of how they apply to polymer variables and end-use requirements.

#### 3.5.1.1 Rheological behaviour of different polymer types

As discussed in Section 3.3, synthetic acrylic polymers can be classified into three groups described here as 'types' according to the following definitions:

- *Type 1*: Products comprised of fully water soluble, essentially linear polymer chains.
- *Type 2*: Products comprised of micron or sub-micron-sized cross-linked polymer particles which are highly swellable by water.

- *Type 3:* Products comprised of water-soluble polymer chains incorporating pendant hydrophobic groups which interact in water to form an ‘associative’ network.

Each of these product types has characteristic behaviours which can be recognised in one or more of the rheological profiles obtained from advanced characterisation methods. These are usually the characteristics which make a polymer well (or badly) suited to the end-use requirements.

3.5.1.2 *Viscosity/shear rate profile*

Probably the most common experiment carried out on aqueous systems containing synthetic polymers is that in which the shear stress is increased from zero to a maximum before being reduced back to zero over a time period of several minutes or more. The rotational speed of the sensor is recorded in line with the applied stress throughout the course of the experiment, so that shear rate data can be calculated. A plot of shear stress versus shear rate obtained in this way is often referred to as a flow curve as shown earlier in Figure 3.8. As already discussed, viscosity equals shear stress divided by shear rate. A viscosity profile is shown by the viscosity value versus shear rate.

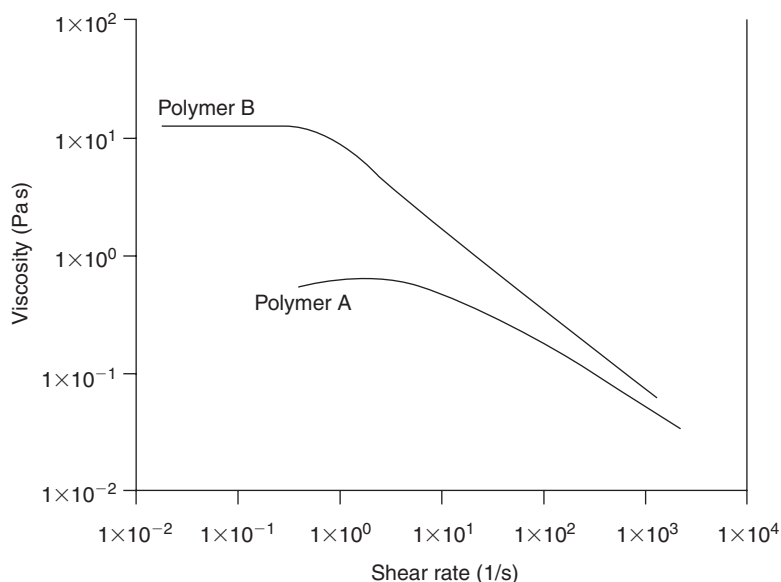
Recalling the range of shear rate values (see Table 3.2) that a paint or cosmetic formulation may be exposed to during manufacture, storage and use, it is apparent that this sort of measurement should cover values ranging over several orders of magnitude or more for both viscosity and shear rate. It is common to see this information presented graphically as log viscosity versus log shear rate.

A comparison of the data from the ‘up’ curve and the ‘down’ curve can reveal information on whether the stress applied to the sample has caused any change in properties of the sample that is not recovered during the measurements for the ‘down’ curve. This would manifest itself as a significant difference in the position of the ‘up’ curve and ‘down’ curve on the graph and is referred to as the ‘hysteresis loop’. Such behaviour is seen in two phase systems such as emulsion paints where, in addition to the contribution to viscosity of the aqueous phase from the polymeric thickener, particle–particle interactions arising from the pigment and latex components can add to the apparent viscosity of the formulation ‘in the can’. This contribution to viscosity is usually destroyed during the process of generating data for the ‘up’ curve and it is not recovered sufficiently quickly to make the same contribution during the ‘down’ curve part of the experiment.

A recent exercise [30] examined polymers selected to be representative of each of the three product types referred to above and the information presented in the graphs which follow is taken from this study. Details of the polymers used are given below:

Type 1	Polymer A	30:70 (w/w) sodium acrylate/acrylamide copolymer	IV = 8.1
	Polymer B	30:70 (w/w) sodium acrylate/acrylamide copolymer	IV = 15.2
Type 2	Polymer D	Cross-linked sodium acrylate homopolymer in LDP form	
Type 3	Polymer E	40:50:10 methacrylic acid/ethyl acrylate/C18 (EO)10 allyl ether	

When solutions of fully water-soluble Type 1 polymers are investigated using a flow curve experiment, it is possible to see a classic ‘double plateau’ profile in the viscosity versus shear rate profile. An upper Newtonian viscosity plateau exists at very low shear rates. This is



**Figure 3.9** Graph 3: Viscosity versus shear rate type 1 polymers.

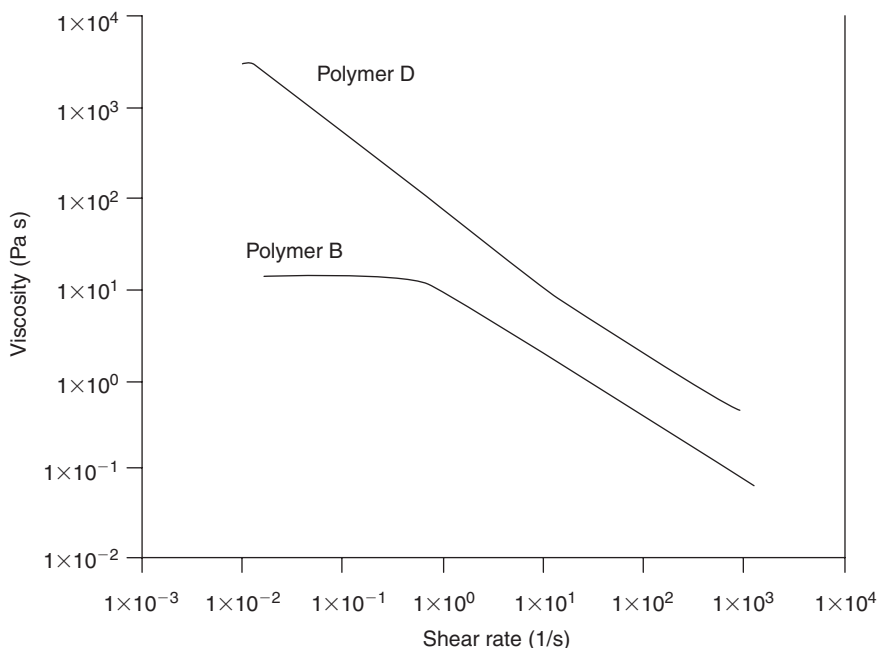
thought to reflect the situation where the polymer chains are in a state of maximum entanglement and contribute the highest possible viscosity to the continuous phase. As the shear stress is increased, the chains respond and orientate along the lines of flow becoming less entangled, which results in a lower contribution to viscosity. The measured viscosity continues to drop as the stress increases until a second equilibrium state, the lower Newtonian plateau, is reached. At this point, further increases in shear force do not result in any further disentanglement or reconfiguration. If the sample is being subjected to a cycle of shear stress, the viscosity starts to increase again as the stress is reduced during the 'down' curve part of the experiment.

The viscosity/shear rate properties are shown in Figure 3.9 for Type 1 products of differing intrinsic viscosity, designated Polymer A and Polymer B (note that only the 'up' curve data are shown on this graph).

The high shear rate lower Newtonian viscosity region is not particularly obvious in this experiment as the shear rate required for this effect to show was not reached under the conditions used. It is important to note that for extremely high molecular weight linear polymers with very high shear forces can generate sufficient stress to cause mechanical degradation through scission of the polymer chain backbone. If this occurs, a proportion of the contribution to viscosity from the polymer is lost permanently.

The Type 2 products comprising cross-linked polymers micro-particles, highly swollen by water, have a different profile. Figure 3.10 compares the profile of Polymer B (Type 1) with Polymer D (Type 2). The cross-linked polymer shows shear thinning behaviour across a very wide range of shear rates with little evidence of either Newtonian Plateau. Both these plateau regions may exist, but the extreme limits of instrument conditions may be needed before these are apparent on the viscosity versus shear rate graph.

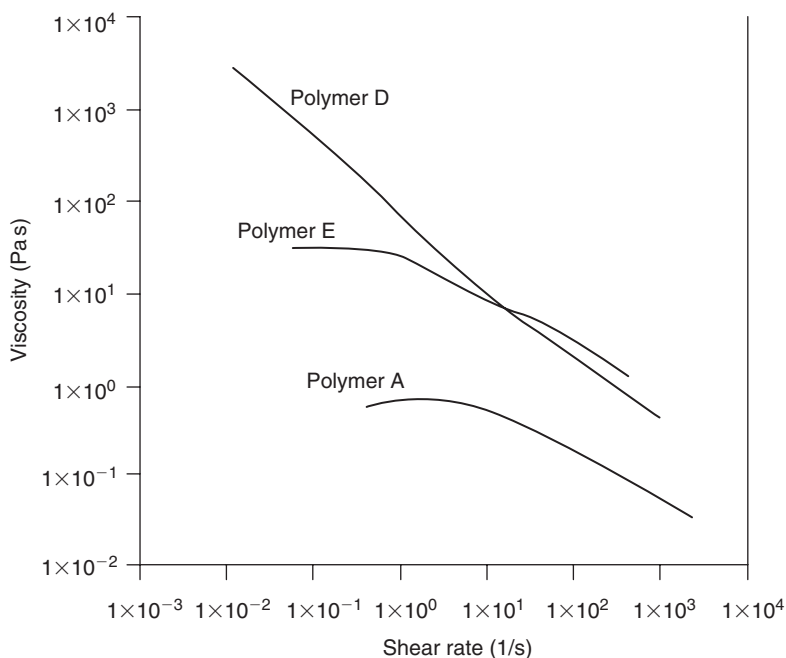




**Figure 3.10** Graph 4: Viscosity versus shear rate for type 1 and type 2 polymers.

When a polymer from the Type 2 group is present in a water-based environment, the particles swell rapidly. The water is absorbed into the matrix of the cross-linked polymer network which forms each particle. Little, if any, 'free' water exists in the interstitial region and each of the swollen particles is in contact with a number of neighbouring particles according to packing geometry considerations. When a shear force is applied, the swollen particles slide past one another quite readily, resulting in the exceptional shear thinning behaviour shown in Figure 3.10. Once the applied force is removed the particles immediately return to an 'at rest' condition. This sort of behaviour is particularly well suited to end uses that require the thickener to provide stability against settlement or creaming under long-term storage (note the very high viscosity value under low shear rate conditions), whilst exhibiting significantly lower apparent viscosity values as the shear rate is increased. Examples of this would be cosmetic creams and lotions as well as pigmented print paste formulations for textiles.

In contrast to both these profiles, the Type 3 polymers (based on hydrophobically modified or 'associative' polymer chemistry) extend the options for the formulation chemist by providing rheological properties which differ again from two groups considered above. As discussed in Section 3.3.2.2, this type of hydrophobically modified acrylic thickener is usually available as a water-based emulsion polymer, which has to be neutralised to provide solubility in water. Once in solution, the hydrophobic groups aggregate as clusters resembling surfactant micelles. The numerous 'anchor points' that exist throughout the solution constrain the movement of the 'host' acrylic polymer chains and act to give a significant boost to the thickening efficiency of such materials compared to their non-associative counterparts. This is important as the lower molecular weight/shorter backbone chain length typical of polymers



**Figure 3.11** Graph 5: Viscosity versus shear rate for type 1, type 2 and type 3 polymers.

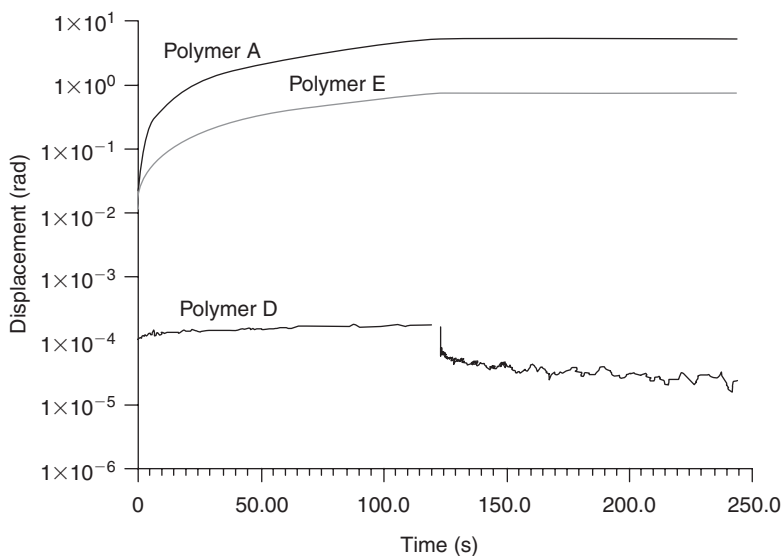
prepared in this form otherwise detracts from their effectiveness as thickeners. This type of behaviour in solution has been shown earlier in Figure 3.1 (see page 43).

The micellar structure exists in a state of dynamic equilibrium in which any one component may leave or join the cluster. This provides for some degree of independent movement of the backbone polymer chain given an appropriate timescale. The clusters hang together with great tenacity and offer significant resistance to any force attempting to disrupt this condition. Not surprisingly, this behaviour manifests itself in the viscosity versus shear rate profile. Figure 3.11 shows the viscosity versus shear rate profile for Polymer E in comparison with Polymer A and Polymer D used earlier.

Although shear thinning in nature, Polymer E exhibits significantly less viscosity loss as the shear rate increases. This sort of profile is best suited to coating applications where a viscosity value which prevents overspreading, for example in the high shear environment of applying paint by brush, needs to be balanced against viscosity which exists in the low shear environment when film defects such as brush marks and bubbles must flow out of the film before drying is complete.

### 3.5.1.3 Creep experiments

In a creep experiment, a small constant stress is applied to the sample and the resultant displacement and/or deformation is monitored versus time. Due to the low stress being applied, the resultant shear rate can be in the region of the upper Newtonian viscosity plateau and simple viscous flow will be observed. In other systems, an instantaneous elastic response can be followed by viscoelastic behaviour and, eventually, Newtonian flow.



**Figure 3.12** Graph 6: Creep experiment.

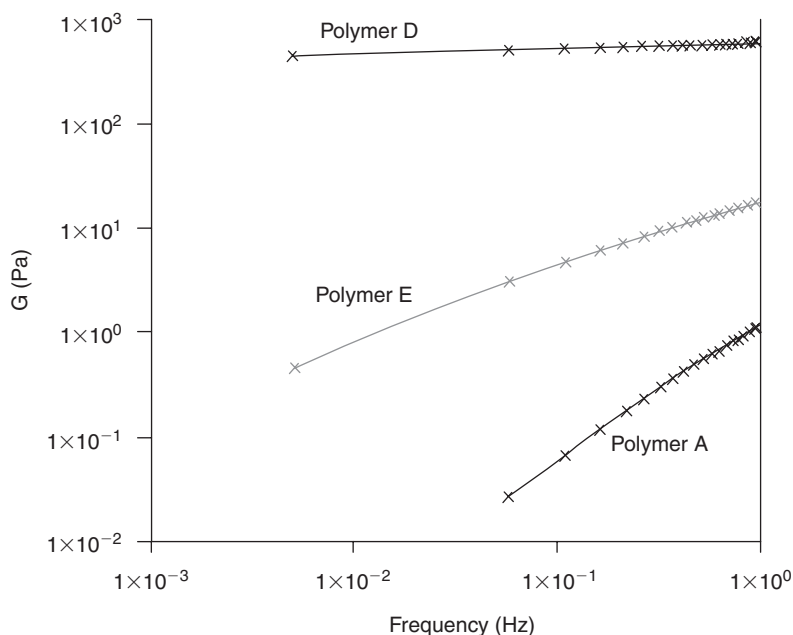
At the end of this experiment, the applied stress is removed although measurements on the sample can continue. If the applied stress has been dissipated by viscous flow no recovery will be observed. If all the applied force has been absorbed elastically, full recovery of the displacement will occur. Viscoelastic materials will show a hybrid response between these two limiting conditions.

The behaviour of products from polymer Types 1, 2 and 3 are shown in Figure 3.12. In this experiment the stress was applied to the samples for a period of 2 min and the behaviour of the samples was monitored for a further 2 min after the stress was removed.

Polymer A and Polymer E exhibit an initial elastic stretch, followed by a region of viscoelastic behaviour. After approximately 60 s, a Newtonian response is seen. No elastic recovery is evident once the stress is removed as the stored elastic response has been dissipated during the timescale of the experiment. In contrast, Polymer D shows less displacement when the stress is first applied, indicative of a more rigid structure. The very shallow gradient of the slope beyond 60 s reflects the very high apparent viscosity under these conditions. Once the stress is removed, a visible elastic recovery is evident from the network within the polymeric micro-particles.

#### 3.5.1.4 Oscillation experiments

Oscillation is a technique useful for the non-destructive testing of structure in materials which can provide additional insight into the properties of polymeric thickeners. The test involves applying a sinusoidal stress wave to the sample and measuring the subsequent strain wave as a response. Purely elastic materials show a zero degree difference in phase between the stress and strain waves. In contrast, purely viscous materials show a 90 degree out of phase behaviour. As already seen in other experimental data, polymeric thickeners have viscoelastic properties. Measuring phase angle differences and the amplitude of the stress and strain waves



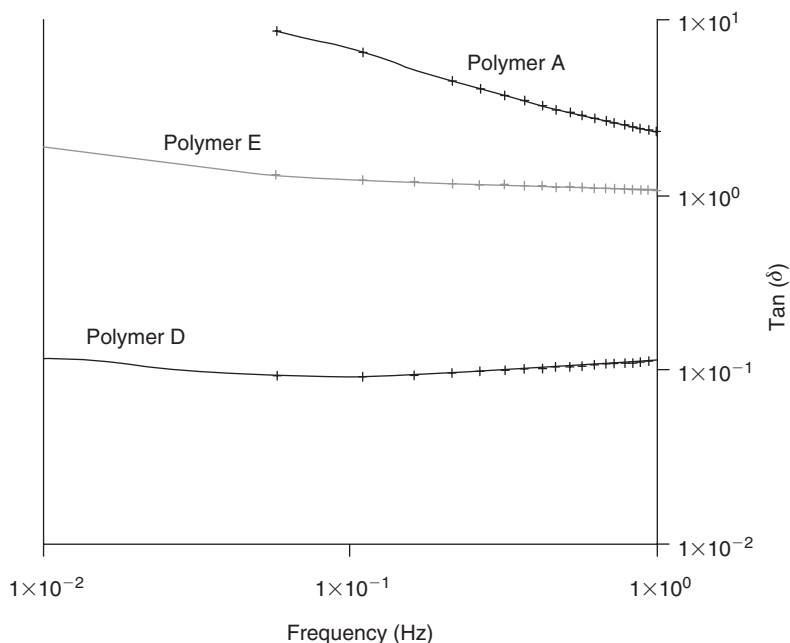
**Figure 3.13** Graph 7: Oscillation study – storage modulus.

allows the instrument software to resolve the viscous and elastic components. Oscillation experiments can be carried out with run time, temperature, torque or frequency being the defined variable. The instrument software is usually set up to use the collected data to carry out the calculations required to present results for the viscoelastic properties, the more commonly used of which are:

- Storage Modulus  $G'$
- Loss Modulus  $G''$
- Dynamic Viscosity  $\eta'$
- $\tan \delta$  (given by  $G''/G'$ ).

Figure 3.13 shows a plot of storage modulus versus frequency for a polymer in each of the three types already described.

Again significant differences are evident. The fully soluble linear product, Polymer A and the associative product, Polymer E, show a marked change in storage modulus with frequency, with the low frequency region showing lower storage modulus values. This arises due to the fact that at low frequencies, the entangled polymer chain network has the opportunity and time to respond to the applied force by independent movement of the chains. As the frequency increases, a point is reached where the response time of the sample to the applied force is longer than the frequency of the applied stress force. Consequently most, if not all, of the force is stored elastically. It is clearly apparent that the cross-linked sample, Polymer D, shows a very high storage modulus value with little sensitivity to frequency, indicating that the polymer network behaves in an elastic manner regardless of the frequency



**Figure 3.14** Graph 8: Oscillation study –  $\tan \delta$  values.

of the applied force. This is supported by the information shown in Figure 3.14 where  $\tan \delta$  is shown versus frequency.

Here it can be seen that Polymer A and Polymer E show  $\tan \delta$  values greater than 1 at all frequencies, whereas Polymer D has a  $\tan \delta$  around 0.1 at all frequencies.

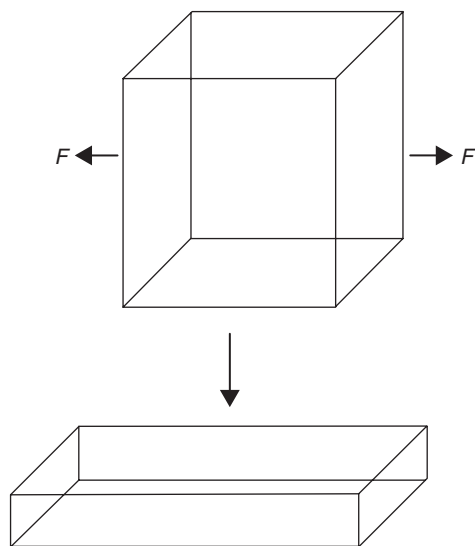
### 3.5.2 Extensional viscosity

So far, consideration has been given to environments where the shearing force applied to the system causes the components to move past one another, but conditions also exist in which the applied force acts in a 'pull' or 'push' manner on the sample where the neighbouring components move away or towards one another as shown in Figure 3.15. The behaviour of polymer solutions under such conditions is best represented by the 'Extensional Viscosity'.

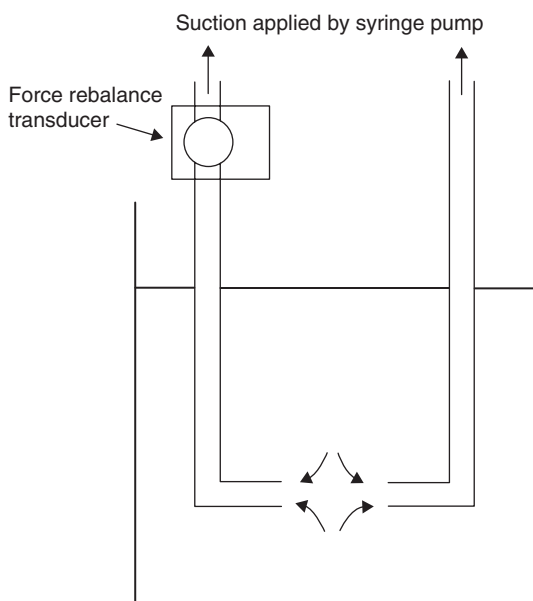
The rotational instruments already discussed do not simulate this sort of condition. Nonetheless, a number of end-use environments exist where extensional flow is the predominant effect. Examples of this are listed below:

- Flow through porous media
- Spattering or misting in roller coating
- Flow into or out of pipes or orifices
- Atomisation during spraying operations.

A value for the rate of extension can be considered as the equivalent to shear rate in flow environments. Actually devising methods which create conditions which can be firstly,



**Figure 3.15** Extensional viscosity behaviour.



**Figure 3.16** Extensional viscometer schematic.

generated reproducibly and secondly, varied in a controlled manner presents a major challenge and this is reflected in the limited number of commercial instruments available for this type of measurement. Options which have been considered include producing filaments or sheets which can be pulled or stretched in one or more directions, but this is of little use

for fluids which do not form 'strands'. An alternative approach was the use of 'opposing jets' immersed in a liquid as shown in Figure 3.16.

This concept relies on liquid flowing into the immersed pipes due to an applied vacuum. The zone in between the orifice to each pipe is a region of significant extensional flow. One of the arms is fixed in position whilst the second is connected to a transducer which measures the force required to keep it in position. Whilst useful in concept, the range of conditions which could be generated by this sort of arrangement was only a limited part of the range which is of practical interest. Although difficult to measure simply and easily under laboratory conditions, extensional viscosity effects play a significant part in the behaviour of synthetic thickeners in many end-use applications. Many of the problems encountered in selecting and optimising synthetic polymers in such situations still rely on an empirical approach, or some form of simulated application test. Work describing the extensional viscosity behaviour of associative and non-associative polymers is available in the literature [31–33].

## 3.6 End-use applications for synthetic thickeners

As already indicated, synthetic polymers are widely used as rheology modifiers in a wide range of industrial processes and formulations. Some of the main uses are discussed in the following section, although this should not be considered an exhaustive review.

### 3.6.1 Oilfield flooding applications

When oil is discovered in an underground reservoir, the initial stage of oil recovery occurs easily due to the inherent underground pressure acting on the field from associated water or gas. This forces oil to the surface via the bore at the production well. This process is known as primary recovery. In secondary recovery environments, additional force is applied to the reservoir to aid further oil recovery. This is necessary when the natural pressure drive in the reservoir has either been depleted or was never sufficient from the beginning. The process usually involves water being pumped underground via an injection well.

Synthetic polymers come into use in oilfield applications once the tertiary recovery stage has been reached. In such situations the use of these additives is appropriate, as a cost effective boost to the viscosity of the injection fluid can give a further enhancement to recovery of oil at the production well. If injection water is able to find an easy route through oil-bearing strata, it will readily follow such channels rather than spreading out along a wide front into areas where oil is still present. This is due, in part, to the fact that water finds it difficult to flow through areas with a high level of oil saturation ( $<40\%$ ). The polymer functions by increasing the viscosity of the injection water such that it is a closer match to the properties of the oil present in the rock strata. This is usually referred to within the industry as having created a more favourable mobility ratio between the oil and water phases. This is particularly critical at the point in time in the life of a reservoir when the efficiency or speed of recovery of the oil has, or is starting to deteriorate.

Also, in reservoirs where there is a lot of variation in permeability (referred to as heterogeneity), the tendency will be for the injection water used in the oilfield flooding operation

to preferentially pass through the highest permeability regions (streaks) [34–36]. A poor match between the viscosity of the oil and the injection water can quickly result in valuable reserves being ‘fingered through’ or by-passed, leading to poor sweep efficiency, early water breakthrough to the production well and inefficiently low oil recovery.

### 3.6.1.1 Key requirements of a polymer for oilfield flooding

- Medium to high molecular weight – important for cost effectiveness.
- Linear polymer chain characteristics – good solubility is important for high injectivity (i.e. no blockage of pores or channels within rock strata by polymer gel particles).
- Low adsorption onto rock strata (avoids depletion of polymer from solution with the corresponding reduction in effectiveness due to loss of viscosity).
- Good thermal stability (high temperatures are common underground).

### 3.6.1.2 Factors affecting solution viscosity

- Polymer concentration.
- Polymer molecular weight.
- Polymer composition/ionic content (high-charge density usually gives greater viscosity per unit weight of polymer due to electrostatic repulsion effects).
- Temperature.
- Electrolyte content of injection water (high ionic strength results in significant chain coiling of highly charge polyelectrolytes).
- Divalent cations (ions such as magnesium, calcium and barium can result in precipitate formation of polymers containing carboxylic acid groups. Polymers containing sulphonic acid groups are much less susceptible to this problem).
- Prevailing shear rate in injection and flooding process (besides the usual shear thinning behaviour of polymer solutions, extreme shear conditions can result in mechanical degradation of polymer chains).

Typically, a polymer concentration in the range of 500–2000 mg/l is required to achieve a viscosity of up to 100 cP at shear rates corresponding to the flow rate in reservoirs with typical permeability. As described above, flow occurs through tortuous routes or channels of the porous rock strata, and the solution is exposed to a range of forces which impact on both the shear viscosity and extensional viscosity properties of the polymer solution.

## 3.6.2 Drag reduction

Although not strictly a thickening phenomena, drag reduction is a characteristic property that water-soluble polymers have on the properties of solutions or suspensions flowing in pipes or tubes [37–40]. When a fluid flows through a pipe under turbulent flow conditions, frictional drag resulting from the movement of the fluid over the inside surface of the pipe causes a loss in pressure which increases as the downstream distance from the pressure source increases. Where an increase in flow rate through the pipe, or a reduction in power consumption is needed, the use of low concentrations of high molecular weight water-soluble polymers



helps by reducing the frictional drag of the fluid in the pipe. The effect has been related to the extensional viscosity of polymers and the local elongation of polymers [41]. Polymers of the very highest molecular weight usually provide the most pronounced effect, although the potential for shear degradation in such types means that optimum drag reduction performance does not always correspond to the product of highest molecular weight.

### 3.6.3 *Textile printing applications*

The printing of patterns and designs onto textile fabrics is a global industry, and fashion designers have the capability to create complex patterns and images using pigments and dyestuffs covering all parts of the colour spectrum. A recent analysis [42] estimated that over 18 million kilometres of fabric were printed in 2002. Virtually all types of fibre/fabric can be printed due to the wide variety of colouring agents, printing machines and formulation aids which make the printing process economically viable. The competing needs for cost efficiency and flexibility has reduced the range of printing machine in use today and some techniques, such as those based on engraved copper rollers have virtually disappeared. Over 95% of printed textiles are now produced using mesh screens in either flat or cylindrical form. Transfer of the print paste through the screen and onto the fabric occurs through the application of pressure, using a metal bar, blade or some form of 'squeegee'. It is critical that the rheological properties of the print paste formulation are correctly optimised for this sort of application technique.

#### 3.6.3.1 *Pigment printing*

This technique, developed in the 1940s, involves a water-insoluble pigment being applied to a substrate and held in place by a suitable 'binder'. After printing, the binder is cross-linked by a heat treatment, and the pigment becomes trapped in the binder matrix. The disadvantages of this process, such as the adverse effect on fabric handle or feel, limitations with brightness of colour, are greatly outweighed by the advantages of simplicity, low cost and applicability to virtually any textile substrate, including blends of different fibres. Natural thickeners were not particularly well suited to this application, due to the stiff handle and poor colour fastness properties. The first synthetic thickeners used for pigment printing were based on powder grades, such as the cross-linked polyacrylic acids discussed in Section 3.3.1.3. These polymers are suitably effective in use but rather difficult to handle due to their dusty nature. Some improvement in physical form of these powders has been achieved, but the last two decades have seen a considerable increase in the use of inverse emulsion and liquid dispersion polymers and these now dominate this application. Aqueous emulsions such as the associative thickeners previously described, tend to find use mainly as 'auxiliary' thickeners.

The ideal thickener for a print paste formulation should meet most if not all of the following requirements:

- Maintain all the components of the paste in a stable suspension.
- Minimal viscosity change on storage.
- Inert to the other components of the print paste.
- Easy removal during the washing processes.

- Must flow through the screen during printing, but recover viscosity rapidly once the shear force is removed.
- Give a sharply defined print without any diffusion into adjacent areas (flushing).
- Good even colour (levelness) of the final print.

The latter two requirements often act in opposition. To achieve a good levelling effect, it is important that the paste is able to flow after it has reached the fabric surface, but to achieve a sharp, well-defined print without flushing, flow after the shear force is removed must be minimal. In practise a compromise is usually required.

### 3.6.3.2 Substantive dye printing

Modern printing machines operate using a liquid formulation in which the dye, together with auxiliary chemicals used for dye fixation, is suspended by a thickener in a formulation prior to application. The dye type is chosen to be specific to the substrate, for example disperse dyes with polyester fabric, acid dyes for nylon, reactive dyes for cotton and regenerated cellulose fibres. Each dye is substantive towards the fibre in question, and fixation is achieved by heat treatment, chemical treatment or both. In almost all cases, the thickener, unfixed dye and any other chemical auxiliaries used in the print paste are removed by a suitable washing process after fixation has been achieved which adds to the complexity and cost of the process. Natural polymers such as starch derivatives, guar gums and alginates are commonly used in this process.

### 3.6.3.3 Synthetic polymers for substantive dyes

Following the successful use of synthetic polymers for pigment printing, the challenge of printing using substantive dyes was investigated. The use of cross-linked polymers based on acrylic acid was known within the industry, but the issue that limited the use of such thickeners was the sensitivity towards electrolyte from simple salts. It became apparent that careful optimisation of the type and level of cross-linking agent had a substantial effect on the performance in this application. Figure 3.17 shows the benefit of carefully optimising the level of cross-linking agent (methylene bisacrylamide) in a polymer based on sodium polyacrylate produced in the form of an LDP at 60% active polymer content, used to prepare two otherwise identical print paste formulations.



**Figure 3.17** Influence of cross-linker level on print quality. Thickener with (a) optimised and (b) non-optimised cross-linker level (images provided by Neil A. Barrett, Ciba Specialty Chemicals).

### 3.6.3.4 *Reactive dye printing*

The demand for articles with superior fastness properties, handle and brightness has led to the increasing use of this class of dye, which is applicable to either cotton or regenerated cellulose fibres. Dye fixation is normally achieved by steaming under atmospheric conditions or, less commonly, by dry heat. This promotes a reaction between the dye and hydroxyl groups on the cellulose substrate to form a covalent bond. Alginate based thickeners are very effective for use with this class of dye due to the tolerance towards electrolyte, although cost effectiveness is sometimes an issue. Although cross-linked synthetic polymers have problems of electrolyte sensitivity as highlighted above, other aspects of their use can allow the dye concentration to be reduced by up to 30% whilst maintaining colour yield and shade. In addition, there are secondary benefits, such as short preparation times for formulations. Alginates may require several hours hydration time before use. Mixtures of alginate and synthetic thickeners have been adopted by many printers.

### 3.6.4 *Emulsion paints and water-based coatings*

Less than 50 years ago, virtually all paint and other surface coating formulations were based on hydrocarbon solvents as the liquid phase. Following advances made in emulsion or latex polymer chemistry, resin systems became available which had the necessary properties of mechanical strength, durability and cost effectiveness such that today, emulsion paint dominates the decorative coatings area. This trend was assisted by the introduction of legislation which discouraged and, in some cases, prohibited the use of formulations which resulted in VOC (volatile organic carbon) emission to atmosphere.

The three main components of emulsion paint are:

- *Pigment*: This gives the covering or hiding effect over the uncoated surface. Minerals such as calcium carbonate and kaolin (china clay) are widely used, as is titanium dioxide for exceptional whiteness.
- *Latex*: The film forming resin which acts as the binder between the pigment particles and the substrate. Ethylene/vinyl acetate and styrene/acrylic polymers are well known, and additional monomers are sometimes utilised to obtain the optimum film forming, durability and gloss properties.
- *Water*: the liquid phase in which the pigment and latex are dispersed.

Terms such as 'matt', 'silk', 'satin' and 'gloss' are used to describe the surface finish of the dried paint. This effect is dictated by the ratio of pigment to binder. Due to the significant density differences between the inorganic minerals and the organic polymer forming the latex, this ratio is usually calculated and expressed as the pigment volume concentration (PVC). For a matt paint, the PVC would typically lie in the region of 60–75%, whereas silk paint would be around 35–50%. The PVC would usually be less than 30% in a gloss paint.

Many other minor components are also needed to ensure the formulation is 'fit for purpose' including colouring agent, biocide, antifoam, and sometimes a co-solvent coalescing aid. Various publications are available which provide details on the composition of typical formulations [43]. It can be argued that the most important minor component is undoubtedly the inclusion of a thickening agent which ensures that the sophisticated formulation can be easily applied to the substrate and remain in place until drying is complete.

In such systems the thickener has to meet a number of critical requirements, some of which oppose each other:

- Must give sufficient viscosity during application by brush to avoid tendency to ‘over-spread’. This would result in poor hiding power and require additional coats to be applied.
- Must give sufficient viscosity under low shear conditions such that ‘sag’ of the coating is avoided on vertical surfaces. At the same time, the viscosity under these conditions should not be so high that brush marks and bubbles remain trapped in the coating and remain visible as defects after drying is complete.
- Must avoid ‘stringiness’ and prevent ‘spatter’ or misting when the formulation is applied using a roller.
- Must be sufficiently effective for the use level to have no adverse effects on the final properties of the dried film such as poor water resistance.
- Must have good chemical and physical stability to allow long-term storage of the formulation.
- Must not cause ‘flocculation’ of the dispersed phase components during preparation, storage or application.

In the context of the synthetic polymers considered in this chapter, the requirements defined above restrict the choice of products for this type of application to the water-based alkali-activated polymers discussed in Section 3.2.2 and the hydrophobically modified alkali-activated polymers are now a common choice of synthetic thickener in emulsion paints.

For other water-based formulation such as tile adhesives, cements and grouts, a little more scope exists for selecting polymers in other physical forms. In these end uses, the composition should be easy to apply or spread on such as the rear surface of a tile, whilst having sufficient viscosity to resist the force of gravity on the tile placed on a vertical surface, until drying is complete. This requirement is well met by the extreme shear thinning profile of cross-linked polymers. Consequently, precipitation polymers or alkali-activated polymers are often selected. Inverse emulsions and LDPs less well suited as the small amount of hydrocarbon oil that would be present in a formulation based on this polymer type can be undesirable in the end use.

### **3.6.5 *Cosmetic, toiletry and household formulations***

A large number of ingredients are used in the formulation of cosmetic and toiletry products. Some of these are essential to the formulation, such as surfactants which provide cleaning properties and oils that give a softening or emolliency effect, although some components may be included for ‘promotional’ benefits. Rheology modifiers would usually be included in the list of key ingredients. Any polymer being considered for such use must confer the desired rheological properties to the formulation, both ‘in the bottle’ as well as in use, be fully compatible with all the other ingredients, as well as meeting the expectations of the formulator and end users with regard to visual appearance and ‘texture’ or feel. This can vary between ‘sparkling’ clarity for some shampoo and shower gel products, through to the smooth, creamy appearance of skin care products which rub in easily during application.

In the main, cross-linked products such as the Carbomer range of precipitation polymers, referred to in Section 3.3.1.3 and inverse emulsion/LDP polymers referred to in Section 3.3.2.1 are well suited to the rheological requirements of cosmetic and toiletry formulations.

In terms of chemical compatibility, the Carbomer range, based on acrylic acid polymers, is most compatible with ingredients which are anionic or non-ionic in nature. The effectiveness is usually maximised in systems formulated to be close to pH 7 as this is the environment in which the polymer is fully ionised. This product group is usually the first choice for 'clear' formulations. When working with inverse emulsion or LDP polymers the formulator has the option of selecting either anionic polymer types based on acrylic acid, or cationic polymers based on the quaternised cationic acrylate ester derivatives. Cationic polymers have excellent compatibility with non-ionic and cationic co-ingredients, which are often found in skin and hair care products. This arises due to the fact that cationic materials are highly substantive to the surface of both skin and hair, due to electrostatic attraction effects. Cationic ingredients are therefore used as 'conditioners' to eliminate the 'fly-away' static effect which can arise after hair has been washed with shampoo.

Inverse emulsion/LDP product types usually provide formulations which are opaque, as the oil phase present as the continuous phase in the product as supplied, becomes emulsified as a disperse phase in the formulation. Additional formulating options are available from grades which have hydrocarbon phases chosen to match the requirements of niche end uses. Medicinal grade 'white oils', hydrophobic esters and even silicone oils have been considered as the hydrocarbon phase for these polymers.

Associative thickeners are also useful thickeners for cosmetic and toiletry products. These products types are most compatible with anionic and non-ionic co-ingredients, give clear formulations and work most effectively in neutral or mildly alkaline environments (to ensure the polymer is fully in solution). Associative thickeners also work well in surfactant systems since the hydrophobic groups in the polymer is able to interact with the micelle structure already present in such systems. Some grades are not effective at giving high viscosity under low shear conditions but the use of thickener combinations can address such limitations.

The complexity of balancing all the ingredients and end-use properties of cosmetic and toiletry formulations is well known and a number of reference texts [44–46] are available to assist formulators working in this area.

### **3.6.6 Agricultural spray systems**

In the agricultural industry, the use of pesticides and herbicides for crop protection purposes is well known and when large areas of land under cultivation require to be treated in this way, application by spray from light aircraft or helicopter is often the preferred approach. During the atomisation process to form a spray, some droplets are formed which are small enough to be carried away from the target area by even light winds. This problem, known as spray drift, is of particular concern when herbicides are being applied, as the portion of the spray susceptible to drift can damage adjacent crops or non-target vegetation. The use of glyphosate as an herbicide has increased significantly in recent years as the acreage of cash crops resistant to this active has increased.

It has been shown that the driftable portion of spray can be reduced by the addition of fully water-soluble high molecular weight linear polymers [47] and the performance in use has been stated to be reasonably correlated with extensional viscosity [48]. Non-ionic and low-charge density anionic polyacrylamide types are preferred as these products are generally compatible with pesticide formulations, particularly glyphosate formulations. The absolute efficiency provided by the polymer is dependent on other ingredients in the formulation as these materials can have an effect on the conformation of the polymer in solution.

The very highest molecular weight polymers become increasingly difficult to dissolve in solid grade form when this is attempted directly in the tank mix prior to spraying. Products which are required for use in this way are therefore often supplied as inverse emulsions or LDPs in order to provide easier dissolution of the polymer.

Surfactants are a useful component in agricultural spray formulations as they improve the penetration of the active ingredient through the leaf cuticle by modification of the surface tension. Surfactants also have an effect on spray drift and droplet bounce. The incorporation of high molecular weight polymers in spray formulations has also been shown to improve the deposition of spray droplets onto crops by reducing the degree of droplet bounce [49]. A combination of surfactants and water-soluble linear polymers can be used to improve the overall efficiency of spray formulations through drift control, improved wetting and reduced droplet bounce, provided the formulation scientist has a good understanding of the interactions between surfactants and polymers and how these can be exploited for optimum benefits [50].

### 3.7 Conclusion

The predictable and reproducible control of rheological properties is a key requirement in many industrial processes and end user formulations. This chapter has attempted to show how acrylic chemistry can be exploited by the polymer scientist to produce a wide range of polymers of differing chemical types, in a number of physical forms with properties intentionally designed to control the rheological properties of water-based systems in a variety of different ways. The formulation scientist and process technologist now have readily available, cost effective, easy to use rheology modifiers which behave in a known and reproducible manner. A basic understanding of acrylic polymer chemistry and the science behind the measurement of rheological properties is very important if the optimum solution is to be found to problems related to the proper control of viscosity in processes and formulations. This chapter may provide one of the starting points in such a journey of learning.

### Acknowledgements

I would like to thank my colleagues in the R&D Department of Ciba Specialty Chemicals, Bradford, UK who provided some of the information used in the preparation of this chapter. In particular, I would like to recognise the assistance given by Neil Barrett, Jackie Casagrande, Brian Dymond, Rebecca Farnell, Bernice Ridley and Simon Rose. A special thank you is due to Narda Gillis who was a great help in compiling the diagrams and text.

## Appendix:

**Table 3.3** Manufacturers and suppliers of synthetic polymeric thickeners

Manufacturer	Trade name	Application area
BASF	Collacral®	Paints and coatings
	Lutexal®	Print paste thickener
	Latekoll®	Coating colours
	Luvigel®	Cosmetics
Ciba Specialty Chemicals	Alcoflood®	Improved oil recovery
	Alcoprint®	Textile print pastes
	Rheovis®	Paints and coatings
	Salcare®	Cosmetics and toiletries
	Viscalex®	Paints and coatings
	Tinovis®	Household formulations
Cytec Industries	Cyanatrol®	Improved oil recovery
	Cyanaflo®	Improved oil recovery
SNF Floerger	Floprint	Textile print pastes
	Flocare	Cosmetics and toiletries
Lanxess	Tanaprint®	Fabric printing
	Acraconz®	Textile print paste
National Starch	Structure®	Cosmetic and toiletries
Noveon	Carbopol®	Cosmetics and toiletries
	Novemer®	Cosmetics and toiletries
	Pemulen®	Household formulations
Rohm & Haas	Acusol™	Paints and coatings
	Aculyn™	Cosmetics and toiletries
Stockhausen	Praestol®	Improved oil recovery

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## Chapter 4

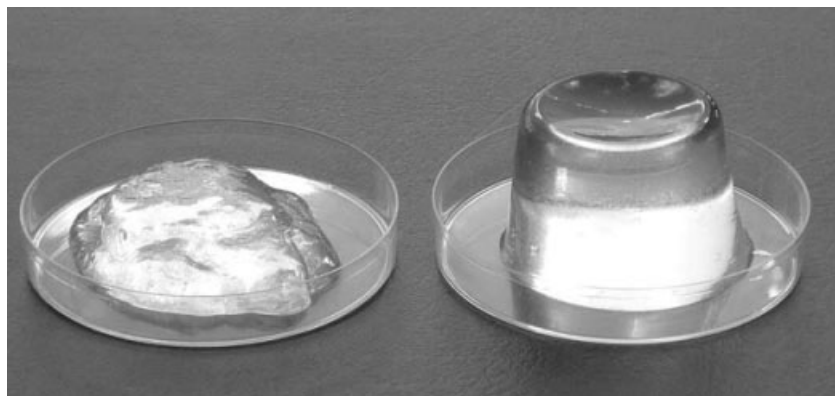
# Gelling Agents

*Peter A. Williams*

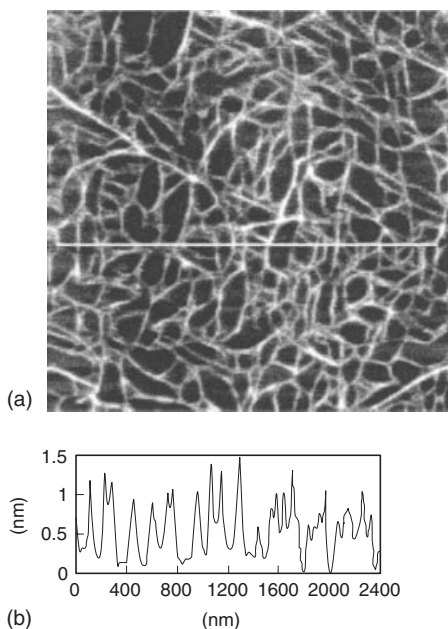
### 4.1 Introduction

A number of water soluble polymers have the ability to form gels [1–6]. The gels may be weak and unable to support themselves or strong such that they retain their shape on removal from their container (Figure 4.1). The gels are referred to as ‘physical gels’ since they are formed by intermolecular association through, for example, hydrogen bonding, hydrophobic association or ion-mediated cross-linking and should be differentiated from chemical gels which can be formed by covalent cross-linking of polymer chains using chemical reagents such as epichlorohydrin and glutaraldehyde. The physical association leads to the formation of a three-dimensional network structure as illustrated in Figure 4.2, which shows a micrograph of a gel formed by gellan gum obtained by atomic force microscopy [7].

Intermolecular association of the polymer chains gives rise to the formation of junction zones and their lifetime will depend on the number of polymer segments that are involved. For some polymers, chain association is a cooperative process with several consecutive segments involved and this leads to the formation of strong gels. Certain helix forming biopolymers, for example, agarose, carrageenan, gellan gum and gelatin, form strong gels on cooling [6]. These polymers adopt a disordered conformation at high temperatures but on cooling undergo a conformational change and stiff ordered helices are formed which self-associate to form a gel. The process is thermally reversible and the gels melt on heating. The melting temperature is often higher than the gelation temperature since melting only occurs after disaggregation of the helices. Other biopolymers, such as alginate and pectin form strong



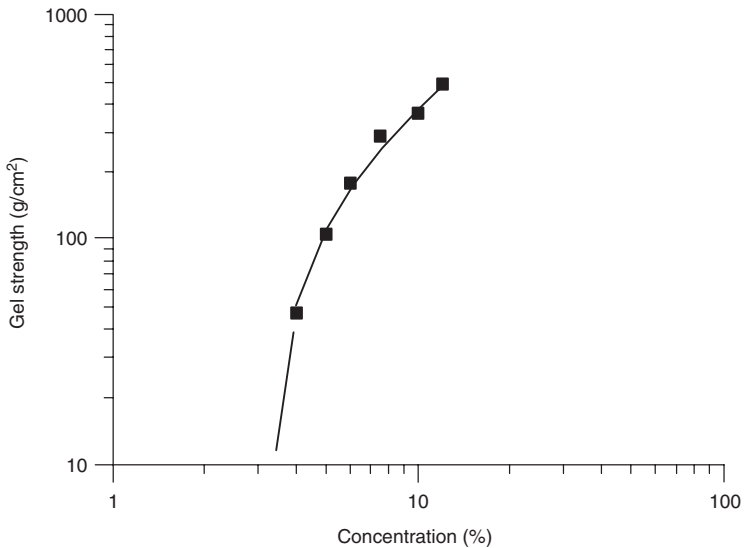
**Figure 4.1** Illustration of weak and strong polymer gels.



**Figure 4.2** Atomic force microscopy (AFM) image of a gellan gel. The graph beneath the image represents the height profile of the section highlighted in the image. Reprinted from [7]. Copyright 2004, with permission from Elsevier.

gels through cation-mediated cross-linking. The cations, e.g. calcium ions, interact with the carboxylate groups on a polymer chain and induce intermolecular cross-linking. The junction zones formed are strong and the gels tend to be thermally irreversible. In contrast some polymers, for example, polyvinyl alcohol (PVA) and galactomannans (e.g. guar gum) form weak gels in the presence of borate ions which are unable to retain their shape and are self-healing [8]. The junction zones formed involve fewer segments and hence are weaker and have a much shorter lifetime. Globular proteins, are able to form gels on heating as a consequence of molecular unfolding [9]. This process leads to the exposure of hydrophobic regions within their internal structure which then undergo intermolecular association giving rise to network formation. Triblock copolymers consisting of polyethylene oxide–polypropylene oxide–polyethylene oxide blocks (PEO–PPO–PEO) can also form gels [10]. These systems adopt micellar structures in solution, which for a given concentration self-associate on increasing the temperature to form thermoreversible gels.

Gel formation only occurs above the critical minimum concentration required to give connectivity,  $C_0$ , which is specific for each polymer type [11]. Agarose, for example, will form gels at concentrations as low as 0.2% while for acid-thinned starch and PEO–PPO–PEO block copolymers a concentration of  $\sim 15\%$  is required before gels are formed. Below  $C_0$  precipitation often results. Figure 4.3 shows the gel strength as a function of sago starch concentration [12].  $C_0$  is  $\sim 3.5\%$  and the gel strength is proportional to  $C^{2.0}$  which is typical for biopolymers [11]. The properties of individual polymer gels vary considerably in strength and elasticity due to differences in the number and nature of the junction zones and the degree of chain aggregation. The main polymer gelling agents and their characteristics are summarised in Table 4.1.



**Figure 4.3** Gel strength of sago starch after 6 h as a function of concentration (from Ref. [12]).

**Table 4.1** Polymer gelling agents

#### Gelation on cooling solutions

##### *Gelatin*

Undergoes a coil-helix transition and forms thermoreversible gels on cooling. Gels are elastic and melt at body temperature.

##### *Agar*

Undergoes a coil-helix transition and forms thermoreversible turbid, brittle gels on cooling ( $\sim 40^{\circ}\text{C}$ ). Gels melt only at high temperatures ( $\sim 85^{\circ}\text{C}$ ).

##### *Kappa carrageenan*

Undergoes a coil-helix transition and forms thermoreversible slightly turbid gels on cooling to  $40\text{--}60^{\circ}\text{C}$ , which is promoted by the presence of electrolyte. Potassium ions are particularly effective due to specific binding to the helices. Melting occurs at  $5\text{--}20^{\circ}$  above the gelation temperature. Gels tend to be brittle and hence it is often used in combination with locust bean gum, which increases elasticity, improves clarity and reduces syneresis.

##### *Iota carrageenan*

Undergoes a coil-helix transition and forms thermoreversible elastic gels on cooling to  $40\text{--}60^{\circ}\text{C}$ . Gelation is promoted by the presence of electrolyte. Melting occurs  $5\text{--}20^{\circ}$  above the gelation temperature.

##### *Gellan gum*

Undergoes a coil-helix transition and forms highly transparent gels on cooling in the presence of electrolyte. Low acyl gels are brittle and are often not thermally reversible. High acyl gels are elastic and thermoreversible. They set and melt at  $\sim 70\text{--}80^{\circ}\text{C}$ .

##### *Xanthan gum*

Undergoes a coil-helix transition and forms highly elastic thermoreversible gels on cooling in the presence of locust bean gum and konjac mannan. Strong gels, which melt at  $\sim 50^{\circ}\text{C}$  are produced in water. In the presence of electrolyte the gels formed are weaker and form at lower temperatures ( $\sim 40^{\circ}\text{C}$ ).

(Continued)

**Table 4.1** (Continued)

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**Gelation on heating solutions****MC and HPMC**

Form thermally reversible gels on heating. Chain association has been attributed to hydrophobic association of methyl groups. The gelation temperature depends on the methyl and hydroxypropylmethyl content.

**PEO–PPO–PEO triblocks**

Forms thermally reversible gels at high concentrations and low temperatures (25°C) due to the formation of cubic close packing and hexagonal packing of micelles.

**HM pectin**

Forms thermally irreversible gels on heating in the presence of high soluble solids (>50%) due to intermolecular hydrophobic association.

**Globular proteins**

Form thermally irreversible gels on heating. The protein chains unfold and reassociate to form aggregates which in turn generate a three-dimensional network.

**Ion-mediated gelation****PVA (and mannose containing polysaccharides)**

Forms weak thermally reversible gels at room temperature in the presence of borate ions at pH>7.

**Alginate**

Forms thermally irreversible gels at room temperature in the presence of divalent ions (notably calcium)

**LM pectin**

Forms thermally reversible gels at room temperature in the presence of calcium ions at pH 3–4.5.

**Retrogradation****Konjac glucomannan**

Forms very strong thermally irreversible gels in the presence of alkali following deacetylation by association of the polymer chains through hydrogen bonding.

**Amylose and amylopectin**

Form very strong, turbid, thermally irreversible gels due to association of the polymer chains through hydrogen bonding.

**Locust bean gum**

Forms strong thermally irreversible, turbid gels when subjected to several freeze–thaw cycles due to association of the ‘smooth’ galactose deficient regions along the mannose chain through hydrogen bonding.

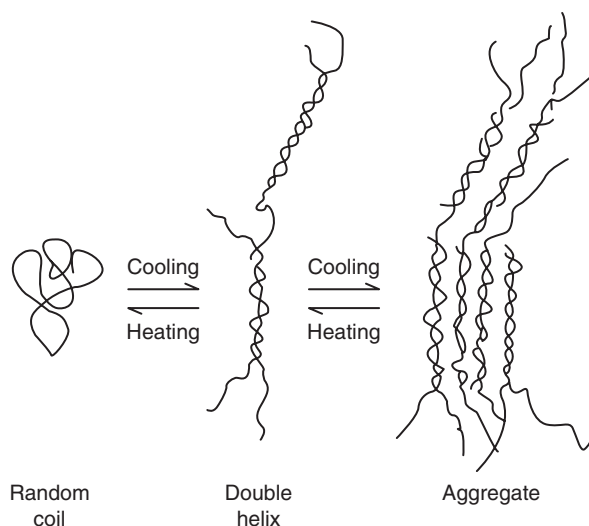
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## 4.2 Gelation triggered by temperature

### 4.2.1 Gels formed on cooling

#### 4.2.1.1 Carrageenan

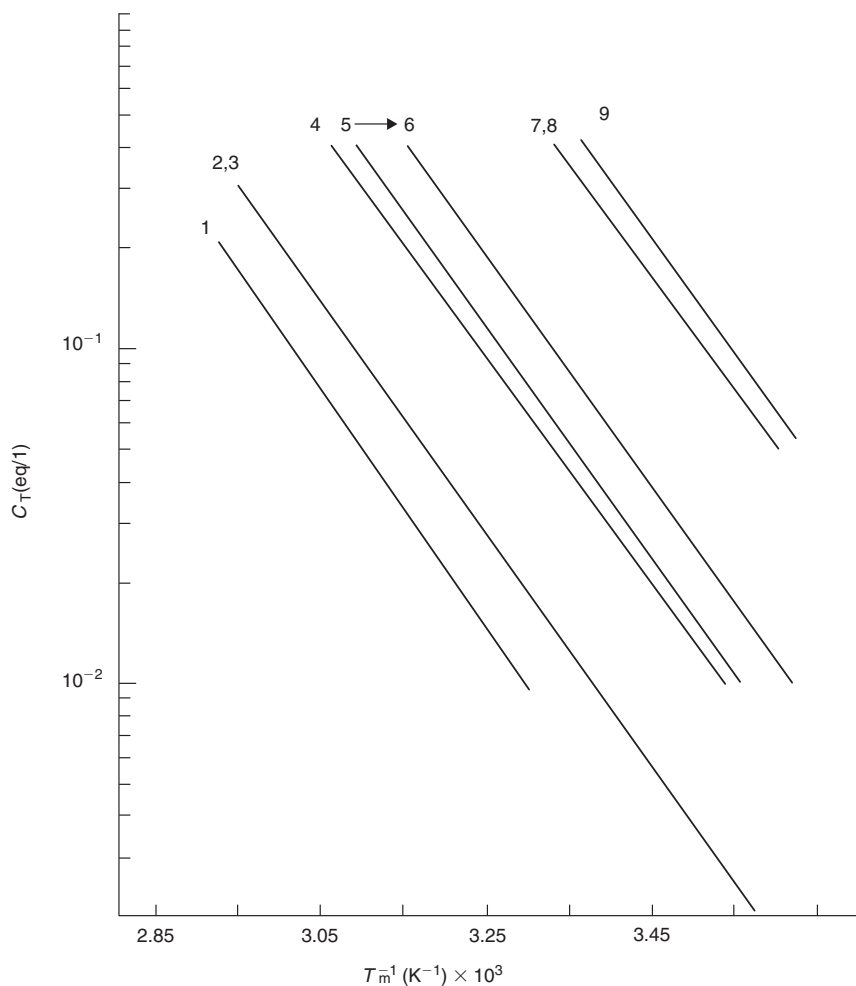
Carrageenans are obtained from red seaweeds (Rhodophyceae) [13, 14]. Traditional carrageenan grades are obtained on extraction into solution by treatment of the seaweed with



**Figure 4.4** Schematic representation of the coil-helix transition of carrageenan and helix aggregation.

hot alkali for 10–30 h followed by precipitation with alcohol or potassium chloride and then drying. A semi-refined product has been introduced in recent years (processed *Euchema* seaweed) which is prepared by treating the seaweed with alkali but avoids extracting into solution and the subsequent precipitation stages. The three major types of carrageenan are kappa, iota and lambda and there is current commercial interest in kappa/iota hybrids. Kappa is obtained from *Euchema cottonii* species and occurs together with lambda carrageenan in *Chondrus crispus*. Iota carrageenan is obtained from *Euchema spinosum*. They differ essentially in their degree of sulphation. The idealised repeat unit for kappa carrageenan consists of (1,3)-linked galactopyranose 4-sulphate and (1,4)-linked 3,6-anhydrogalactopyranose residues. Iota carrageenan differs only in that the latter residue is sulphated at the C2 position. Lambda carrageenan is further sulphated and consists of (1,4)-linked galactopyranose 2,6-disulphate and (1,3)-linked galactopyranose which are 70% substituted at the C2 position. Unlike lambda carrageenan, kappa and iota carrageenan adopt ordered double helical structures as evidenced by X-ray diffraction. While lambda carrageenan forms viscous solutions when dissolved in water, both kappa and iota form thermoreversible gels on cooling. The molecules undergo a conformational coil to helix transition and the helices self-associate giving rise to a three-dimensional gel structure (Figure 4.4).

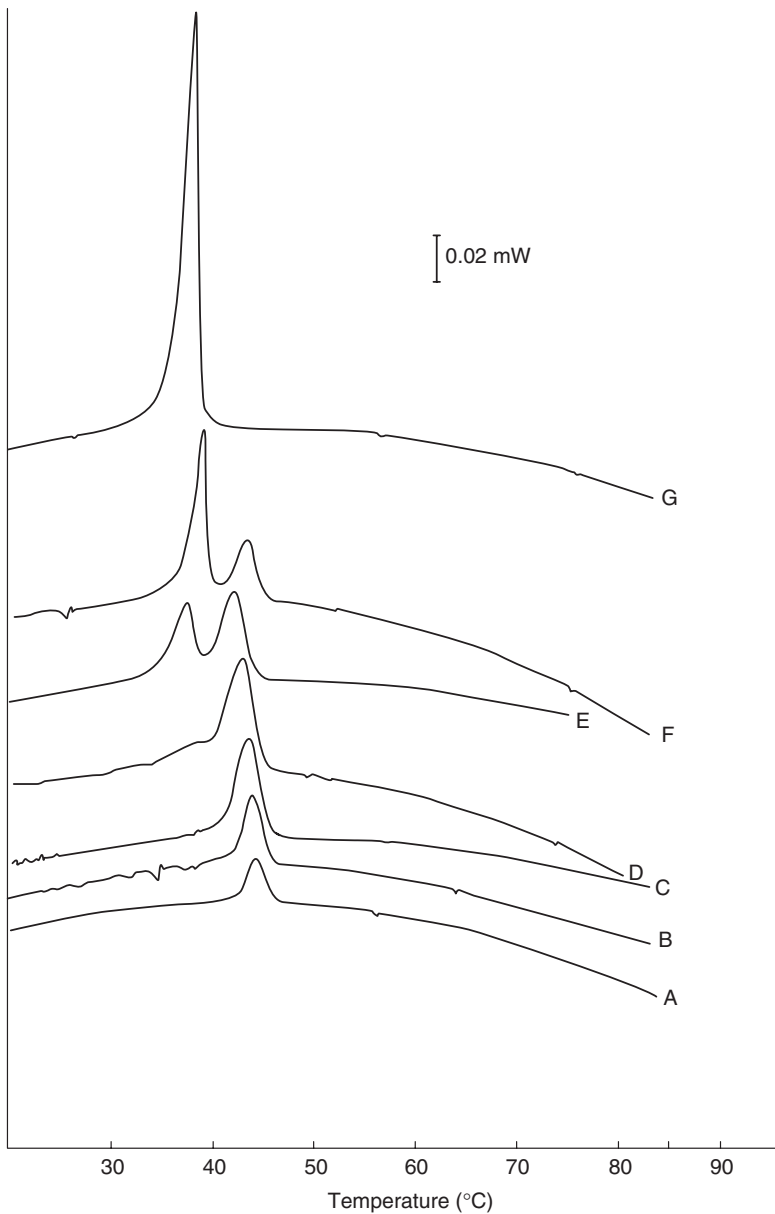
The temperature of the conformational transition (and hence gelation) increases with increasing electrolyte concentration and varies with the nature of the ions added. This is illustrated in Figure 4.5 which plots the total concentration of ions ( $C_T$ ) as a function of  $1/T_m$  (the reciprocal of the midpoint temperature of the conformational transition) [15]. It shows that potassium, rubidium and caesium ions have a pronounced effect compared to other cations. This has been attributed to specific binding of these ions to the helical structure of kappa carrageenan [14]. The nature of the binding site is not clear but may involve a number of oxygen atoms within the helix. The specific binding stabilises the helical conformation and as a consequence, the helices form at a higher temperature and



**Figure 4.5** The influence of cation concentration on the coil-helix midpoint transition temperature. Monovalent ions: 1,  $\text{Rb}^+$ ; 2,  $\text{K}^+$ ; 3,  $\text{Cs}^+$ ; 4,  $\text{NH}_4^+$ ; 7,  $\text{Na}^+$ ; 8,  $\text{N}(\text{CH}_3)_4^+$ ; 9,  $\text{Li}^+$ . Divalent cations: 5–6,  $\text{Ba}^{2+}$ ,  $\text{Ca}^{2+}$ ,  $\text{Sr}^{2+}$ ,  $\text{Mg}^{2+}$ ,  $\text{Zn}^{2+}$  and  $\text{Co}^{2+}$  (from Ref. [15]). With permission from Wiley InterScience.

lower electrolyte concentration in the presence of potassium chloride compared to say sodium chloride. This ion specificity is not observed for iota. The binding of cations reduces the effective charge density of the helical chains and hence promotes helix aggregation and the formation of a three-dimensional gel structure. It is interesting to note that iodide ions also specifically bind to the kappa carrageenan helices [16]. These ions enhance the polymer charge density and prevent helix association and, therefore, gelation.

Kappa carrageenan forms opaque, brittle gels which are subject to syneresis while iota tends to form weaker but more transparent elastic gels compared to kappa. The different gel characteristics are probably due to the fact that the increased charge on the iota carrageenan chains reduces the extent of helix self-association. It has long been known that the properties of kappa carrageenan gels can be improved by the addition of konjac mannan or locust



**Figure 4.6** DSC cooling curves for kappa carrageenan/konjac mannan mixtures (total polymer concentration 0.6%) in the presence of 50 mM KCl. A: 0.1/0.5; B: 0.2/0.4; C: 0.3/0.3; D: 0.4/0.2; E: 0.45/0.15; F: 0.5/0.1 and G: 0.6/0. Reprinted with permission from [18]. Copyright 1993 American Chemical Society.

bean gum [17]. The increased gel strength observed has been attributed to association between the konjac mannan or locust bean gum chains and the kappa carrageenan helices. This conclusion has been supported by differential scanning calorimetry (DSC) studies [18]. Figure 4.6 shows the cooling curves obtained by DSC for kappa carrageenan in the



presence of 50 mM KCl and varying concentrations of konjac mannan. For kappa carrageenan alone (curve G), an exothermic peak was observed with a midpoint transition temperature of 40°C. This corresponds predominantly to the coil-helix conformational transition and to a lesser extent helix association and gel formation. For carrageenan-konjac mannan mixtures with carrageenan in excess (curves D, E and F) two peaks are observed, namely at 43.5°C and 40°C. The higher temperature peak corresponds to the coil-helix transition of the carrageenan and subsequent association with konjac mannan, while the lower temperature peak corresponds to the coil-helix transition of the excess carrageenan. When the konjac mannan is in excess (curves A, B and C) the lower temperature peak disappears since all of the carrageenan present is interacting with the konjac mannan.

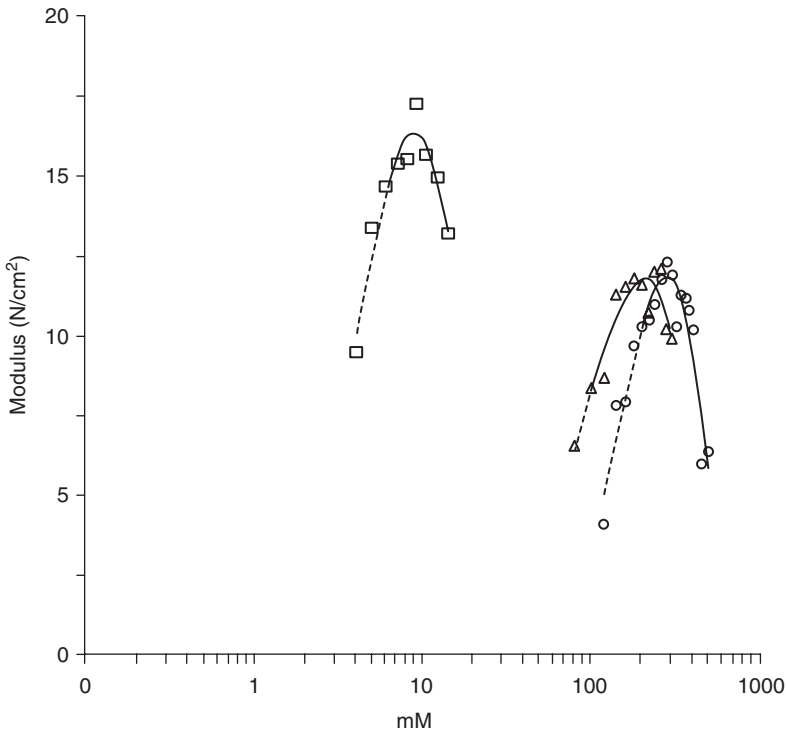
Carrageenans find widespread use in the food industry notably in meat and dairy products. They are also used, for example, in air fresheners to control the rate of release of the fragrance.

#### 4.2.1.2 Agarose

Agarose (the major component of agar) is also obtained from red seaweeds notably *Gelidium* and *Gracilaria* species [19, 20]. It is a linear neutral polysaccharide and has a similar structure to the carrageenans consisting of alternating (1,3)-linked  $\beta$ -galactopyranose and (1,4)-linked 3,6-anhydro- $\alpha$ -galactopyranose unit. It dissolves in near boiling water and gels on cooling to  $\sim 35$ – $45^\circ\text{C}$  depending on the source. The agarose molecules adopt a random coil conformation at high temperatures and double helices are formed on cooling. Gelation occurs as a consequence of helix formation but, since the agarose chains are non-ionic, extensive helix aggregation occurs resulting in the formation of very strong gels which melt only on heating to  $80$ – $90^\circ\text{C}$ . The properties of agarose gels can be modified by the addition of locust bean gum or konjac mannan as is the case for kappa carrageenan and a similar mechanism has been proposed. Agarose finds application in food products and is used by microbiologists as a matrix to grow bacteria.

#### 4.2.1.3 Gellan gum

Gellan gum is a bacterial polysaccharide produced from *Sphingomonas elodia* by aerobic fermentation and consists of a linear tetrasaccharide repeat unit of  $\beta(1,3)$ -glucopyranose,  $\beta(1,4)$ -glucuronopyranose,  $\beta(1,4)$ -glucopyranose and  $\alpha(1,4)$ -rhamnopyranose [21]. In the native form the  $\beta(1,3)$ -glucose residues contain glycerate and acetate moieties positioned on the O(2) and O(6), respectively. On average there is 1 glycerate and 0.5 acetate groups per repeat unit. X-ray fibre diffraction studies indicate that the gellan molecules form a 3-fold double helical structure and in solution undergo a thermoreversible coil-helix transition. As with carrageenan the transition shifts to higher temperatures in the presence of electrolyte. The helices, once formed, self-associate leading to the formation of highly transparent gels. Gel strength increases with increasing salt concentration until a maximum is reached. Further addition of salt results in a reduction in gel strength due to polymer precipitation. Gelation occurs at lower concentrations in the presence of divalent ions compared to monovalent ions and the gels tend to be stronger as illustrated in Figure 4.7 [21]. Gels formed in the presence of monovalent ions are usually thermally reversible although the melting temperature is normally much greater than the gelation temperature, a consequence of extensive molecular aggregation. If gels are formed by the addition of divalent



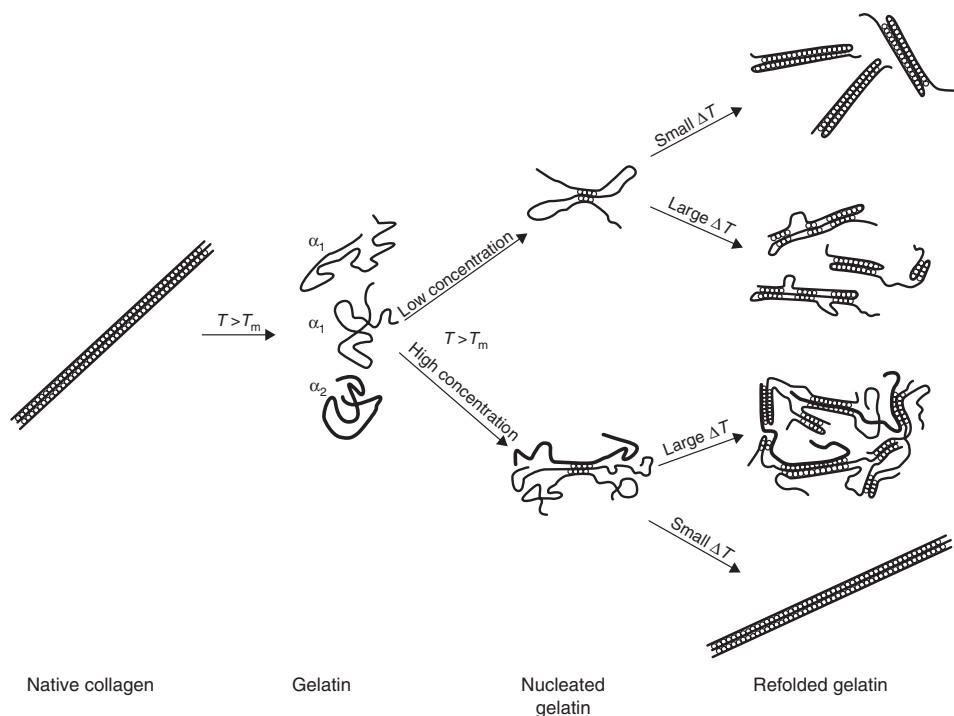
**Figure 4.7** Modulus of gels of gellan gum in the presence of varying concentrations of calcium (squares), sodium (triangles) and potassium (circles) ions (adapted from Ref. [21]).

ions then they can be thermally irreversible. The native form produces soft elastic gels whereas the deacetylated material sold commercially forms hard brittle gels.

Gellan gum is still relatively expensive and hence finds limited application at present in food products such as dessert jellies, sugar confectionery and fruit preparations.

#### 4.2.1.4 Gelatin

Gelatin is derived from collagen, which is a protein and a major constituent of the white fibrous connective tissue occurring in the hides, skins and bones of animals [22]. It is obtained mainly from cattle and pigs although since the outbreak of BSE in the 1990s alternative sources, notably fish skins, have been investigated for application in foods and pharmaceuticals [23]. Collagen has a triple helical structure with a molecular mass of  $\sim 300,000$ . On heating the chains unfold to yield  $\alpha$ ,  $\beta$  and  $\gamma$  chains. The  $\alpha$  chains have a molecular mass of  $\sim 100,000$  and the  $\beta$  and  $\gamma$  chains consist of two and three covalently bound  $\alpha$  chains respectively. The main amino acid is glycine which accounts for approximately one-third of the total followed by proline and hydroxyproline. The collagen is extracted from the raw material by either acid or alkaline treatment. Acid treatment involves immersing in cold dilute mineral acid (pH 1.5–3.0) for up to 30 h while for alkaline treatment the raw material is steeped in saturated limewater (pH 12.0). The material is then



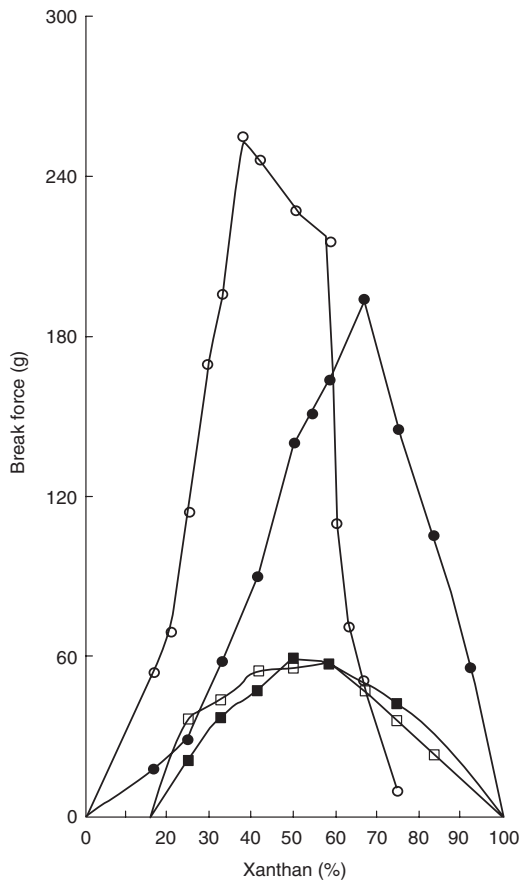
**Figure 4.8** Schematic representation for the concentration-dependent dual pathway for chain folding below the setting temperature ( $T_m$ ). Reprinted with permission from [24]. Copyright 1970 American Chemical Society.

washed with water leading to the isolation of Type A (acid treatment) and Type B (alkaline treatment) gelatins. Type A gelatin contains lower amounts of glutamic and aspartic acids and hence the isoelectric point for Type A is in the range 7–9.4 while for Type B it is in the range 4.8–5.5. In solution above  $\sim 40^\circ\text{C}$ , the gelatin molecules are in the form of random coils but on cooling the chains tend to order to form collagen-like triple helices which aggregate to form optically clear elastic gels. A schematic of the gelation process is given in Figure 4.8 [24]. It has been suggested that regions with the glycine–proline–proline sequence tend to take up the proline–L-proline II helix conformation and are involved in junction zone formation. The gels are thermoreversible and melt on heating to  $\sim 35\text{--}40^\circ\text{C}$ .

Gelatin is widely used in the food industry notably in confectionery, meats, dairy and dessert products. It has major application in the pharmaceutical area where it is used to prepare capsules and also in photography where it is used to adhere the photosensitive silver halide onto paper or film. It is also used in the production of holograms.

#### 4.2.1.5 Xanthan gum

Xanthan gum is a bacterial polysaccharide obtained from the genus *Xanthomonas*, notably *X. campestris* by aerobic fermentation [25]. The molecules have a  $\beta(1,4)$ -linked glucopyranose backbone with a trisaccharide side-chain on every other glucose residue linked through the C3 position. The side-chain consists of two mannopyranosyl residues linked on



**Figure 4.9** Gel strength as a function of xanthan concentration for mixtures with locust bean gum (squares) and konjac mannan (circles) in water (open symbols) and 40 mM NaCl (closed symbols). Reprinted from [27]. Copyright 1991, with permission from Elsevier.

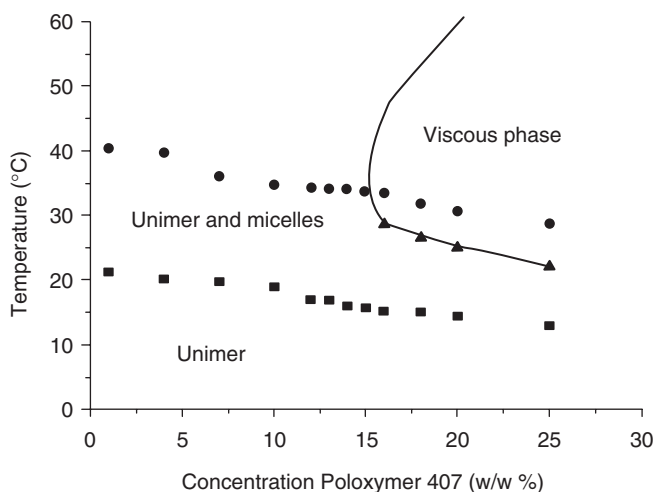
either side to a glucopyranosyl uronic acid group. The inner mannose residue connected to the backbone may be acetylated while the terminal mannose residue may be pyruvated. The xanthan molecules undergo a thermoreversible coil–helix transition in solution, which shifts to higher temperatures by the addition of electrolyte [26]. In the disordered coil form the side-chains are envisaged as protruding away from the backbone into solution, while in the ordered form the molecules form a stiff 5-fold helical structure with the side-chains folded in and associated with the backbone. It is now generally recognised that the helix consists of two xanthan chains. Although xanthan gum alone does not form gels it is well known that thermoreversible gels are produced in the presence of locust bean gum or konjac mannan. This is illustrated in Figure 4.9 which shows the gel strength of xanthan–locust bean gum and xanthan–konjac mannan mixtures in the presence and absence of electrolyte. Stronger gels are formed with konjac mannan and in the absence of electrolyte [27]. It has been argued that gelation occurs due to molecular association of xanthan with locust bean gum and konjac mannan and is triggered by the xanthan coil–helix transition [17, 28, 29]. These gels are now finding application in cosmetic formulations.

## 4.2.2 Gel formation on heating

### 4.2.2.1 Triblock copolymers of PEO–PPO–PEO

PEO–PPO–PEO triblock copolymers are readily available commercially with a range of architectures which has a significant influence on their properties [30, 31]. The Chapter by Prof. Riess in this book provides information on their synthesis and reviews their solution properties. At a given concentration they exist in solution as single entities (unimers) but they will aggregate above a critical concentration (typically  $\sim 1\%$  w/v) to form micelles. The length of the PPO chain is the primary factor in the micellisation process. As the length of the PPO chain increases the critical micelle concentration (CMC) is reduced. Micellisation is also highly temperature dependent. The critical micelle temperature (CMT) can typically vary between 10 and 30°C depending on the stoichiometry of the triblock. The aggregates are believed to arise as a result of dehydration of the PPO chains and are assumed to consist of an inner hydrophobic core of PPO moieties surrounded by hydrated PEO chains. At high concentrations certain triblock copolymers are able to form gels and it is believed that gelation occurs as a consequence of the formation of an ordered array of spherical micelles in a cubic phase or at higher temperatures as rod-like micelles in the form of a hexagonal phase. A typical phase diagram obtained for Poloxamer 407 (PEO<sub>98</sub>–PPO<sub>69</sub>–PEO<sub>98</sub>) is given in Figure 4.10 [32]. It is noted that for this polymer, solutions above  $\sim 15\%$  concentration have a low viscosity at ambient temperatures but form viscous solutions/gels above  $\sim 25^\circ\text{C}$ .

The inner PPO core is able to solubilise hydrophobic compounds and hence they have application in, for example, the controlled release of ‘water insoluble’ drugs. Their ability to form gels on heating to body temperature has led to a number of medical applications, e.g. they are used as an intraperitoneal barrier for prevention of post surgical adhesion formation.



**Figure 4.10** Phase diagram for PEO–PPO–PEO triblock copolymer (Poloxamer 407) (from Ref. [32]).

#### 4.2.2.2 Cellulose derivatives

Methyl and hydroxypropylmethyl cellulose (MC and HPMC, respectively) are produced commercially from cellulose which is obtained from trees and cotton [33, 34]. Cellulose itself is composed of linear chains of  $\beta(1,4)$ -linked glucopyranose units, which associate to form crystalline arrays. Derivatisation involves converting the cellulose to the sodium form by treatment with alkali in order to destroy the crystalline structure. The so-called alkali cellulose is then reacted with the appropriate reagent, namely methyl chloride for MC or methyl chloride and propylene oxide for HPMC. These reagents replace the hydroxyl protons on the sugar rings and since the reactions are heterogeneous, substitution can be very irregular. Each glucose residue has three available hydroxyl groups for reaction. MC and HPMC are supplied in a range of molecular sizes and degrees of substitution. Since the substituted groups may also participate in the reaction a molar substitution (MS) is also quoted to characterise the polymers. MC and HPMC form thermoreversible gels on heating. The number of methyl groups present has the most significant influence on the gel characteristics. As the methyl content increases the gels formed on heating become firmer. The gelation temperature is also dependent on the degree of substitution. For MC containing 30% methoxyl groups, gelation occurs at  $\sim 50$ – $55^\circ\text{C}$  whereas for HPMC containing 20% methoxyl and 8% hydroxypropyl, gelation occurs at  $\sim 85^\circ\text{C}$ . Gelation occurs as a consequence of dehydration of the hydrophobic moieties along the polymer chain and molecular association through hydrophobic bonding.

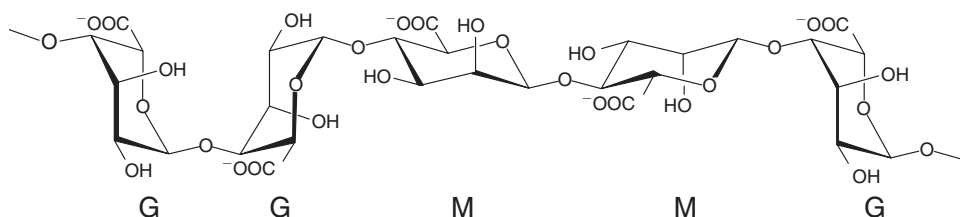
Both MC and HPMC form surface films. They are used in food products as binders and to aid shape retention on heating in products such as reformed vegetables (potato croquettes, onion rings, etc.) and fish cakes. They are also used in personal care products such as shampoos, hair conditioners, shaving gels and toothpaste.

### 4.3 Ion-mediated gelation

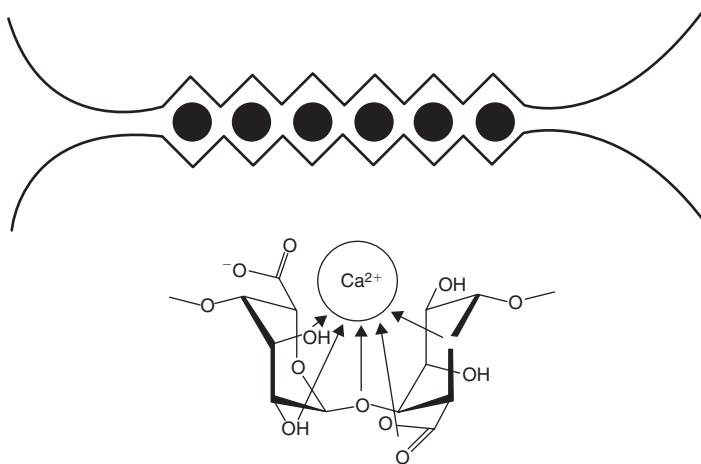
#### 4.3.1 Cation-mediated gelation

##### 4.3.1.1 Alginate

Alginate is obtained from brown seaweeds (Phyophyceae) [35, 36]. Extraction initially involves treating the seaweed with  $\sim 0.2\text{ M}$  mineral acid to convert the insoluble alginate in mixed ion form to alginic acid and then neutralising using sodium hydroxide or sodium carbonate to form soluble sodium alginate. Insoluble material is removed by filtration, centrifugation, etc. and the alginate is then recovered by precipitation using alcohol, calcium chloride or mineral acid. Alginate is a linear (1,4)-linked polyuronan consisting of mannuronic and guluronic acid, which are present as blocks of separate or mixed sequences along the chain depending on the seaweed source. The mannuronic acids are linked equatorially forming linear sequences while the guluronic acids are linked axially giving rise to a buckled structure (Figure 4.11). *Macrocystis pyrifera* and *Ascophyllum nodosum* have a high mannuronic acid content (61% and 65% respectively), whereas *Laminaria hyperborea* has a high guluronic acid content (69%). Sodium alginate dissolves readily in water to form viscous solutions and thermally irreversible gels are formed in the presence of divalent cations (notably calcium).



**Figure 4.11** Mannuronic and guluronic acid residues making up an alginate chain.



**Figure 4.12** Schematic representation of the 'egg-box' model depicting alginate junction zone formation.

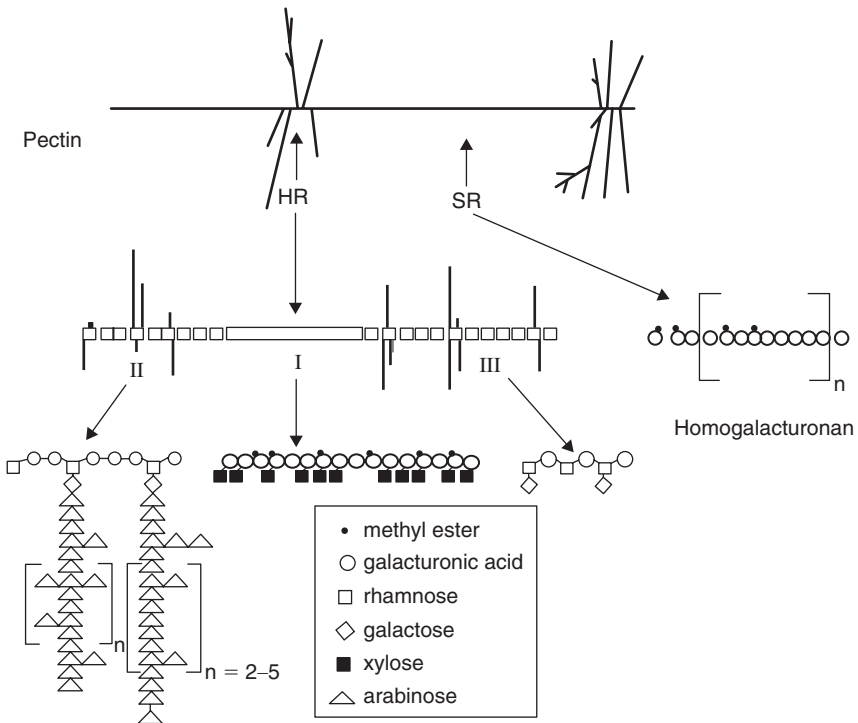
The guluronic acid residues preferentially bind calcium ions and their proportion and distribution along the polyuronan chain have a major influence on the properties of the gels produced. The buckled structure formed by diaxially linked guluronic acid residues provides a strong binding site for cations which interact with the carboxyl and hydroxyl groups. Intermolecular cross-linking of sequences results in the formation of junction zones and a three-dimensional gel network. This mechanism has been described as the egg-box model (Figure 4.12) [36]. The binding of divalent ions is highly pH dependent and increases as the pH increases up to  $\sim 5$ . At pH 5 and above it has been found that binding corresponds to 1 divalent ion per  $\sim 4$  carboxylate groups (i.e. half of the stoichiometric ratio) which is consistent with the 'egg-box' model. Since the spacing between the binding sites is greater than the ionic radii of the cations, it has been argued that the divalent ions form monocomplexes with the carboxylate groups causing charge reversal which then leads to cross-linking [37].

If the divalent cations are added rapidly to sodium alginate in solution inhomogeneous gels are produced. In order to produce homogeneous gels a common practice is to generate the cross-linking ions slowly *in situ*. Sparingly soluble salts such as calcium sulphate are used and the release of ions is controlled by the presence of sequesterants and adjustment of pH.

Alginate is commonly used in the Food Industry in, for example, dairy products, desserts, fruit pie fillings, structured fruit and sugar confectionery. It is used to immobilise enzymes to aid recovery and also it can be spun to produce fibres. Solutions of sodium alginate are forced under pressure through a spinneret immersed in a bath of a soluble calcium salt. When the alginate comes into contact with the calcium solution, gelation occurs and the gel filaments are drawn to form fibres.

#### 4.3.1.2 Pectin

Commercial pectins are obtained from apple pomace or the peel of citrus fruits particularly lemons or limes although orange peel is available in the larger quantities [38–40]. Most pectin is produced by extraction in hot aqueous mineral acid followed by precipitation with alcohol. Pectin molecules consist of linear chains of (1,4)- $\alpha$ -galacturonic acid residues up to 80% of which occur as the methyl ester together with up to 4% (1,2)- $\alpha$ -rhamnopyranose units which are distributed along the chain giving rise to kinks. L-arabinose, D-galactose and D-xylose (10–15%) are linked to the rhamnose units forming ramified side-chains which are referred to as 'hairy regions' along the otherwise smooth galacturonan backbone. This is illustrated in Figure 4.13 which shows linear galacturonic acid chains (smooth region) and the ramified side-chains (hairy regions) [41]. If the degree of esterification (DE) is  $>50\%$  it is referred to as

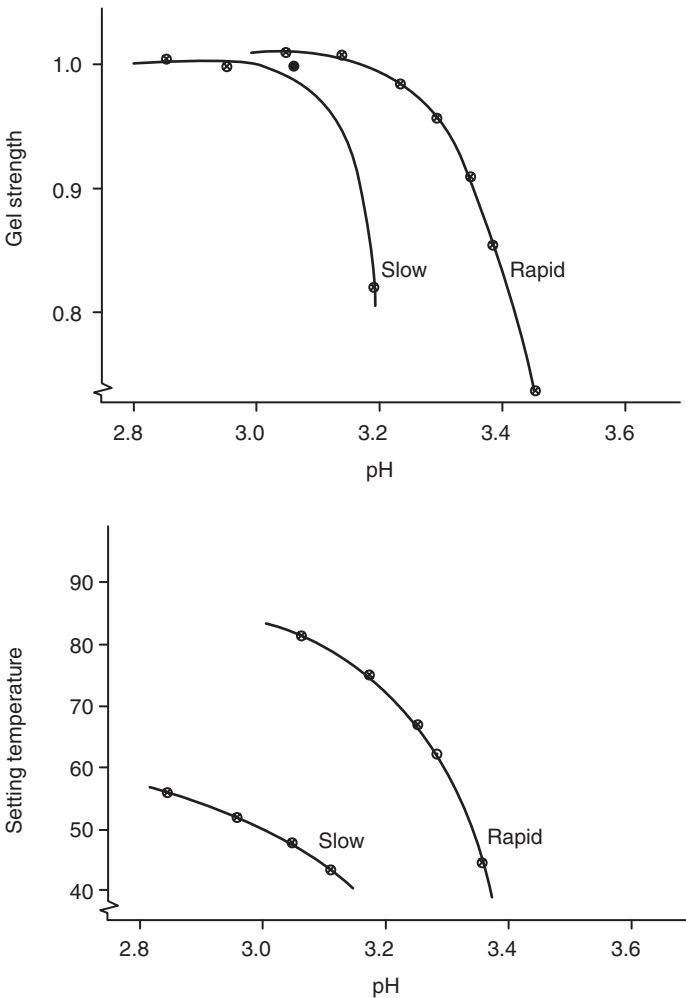


**Figure 4.13** Hypothetical structure of apple pectin showing; I xylogalacturonan region, II region with arabinan side-chains, III rhamnogalacturonan region making up the hairy region (HR). SR is the smooth region (from Ref. [41]).



high methoxyl (HM) pectin. De-esterified pectin with  $DE < 50\%$  is produced by mild acid or alkali treatment and is referred to as low methoxy (LM) pectin. If the alkali used is ammonia, a low methoxyl (LM) amidated pectin is produced.

Pectin is soluble in water and is most stable at pH of  $\sim 3\text{--}4$ . Above and below this value hydrolysis may occur. Both HM and LM pectins form gels. For HM pectin ( $DE\ 60\text{--}75\%$ ) gelation occurs at high soluble solids content (typically  $50\text{--}75\%$  sugar) and at  $pH\ \sim 3.5$  over a period of time. HM pectin with a  $DE$  of  $\sim 70\%$  is referred to as a rapid set pectin and HM pectin with a  $DE$  of  $\sim 60\%$  a slow-set pectin. The strength of HM pectin gels increases with increasing sugar concentration. The variation of the gel strength and gel setting temperature for rapid set and slow set pectins in the presence of  $65\%$  sugar are illustrated in Figure 4.14 [40]. It is noted that the slow set pectin gels at slightly lower pH values and at lower



**Figure 4.14** Effect of pH on the gelation of rapid set and slow set HM pectin (from Ref. [40] with kind permission of Springer Science and Business Media).

temperatures. The gels formed are not thermoreversible. Junction zone formation is believed to be as a consequence of hydrophobic association between ester groups coupled with intermolecular hydrogen bonding between hydroxyl groups on the galacturonan backbone.

For LM pectin (DE typically 20–40%) gelation is brought about by the addition of divalent cations as is the case for alginate. A high soluble solids content and low pH are not a prerequisite for gelation to occur. Gelation is rapid and is usually thermoreversible.

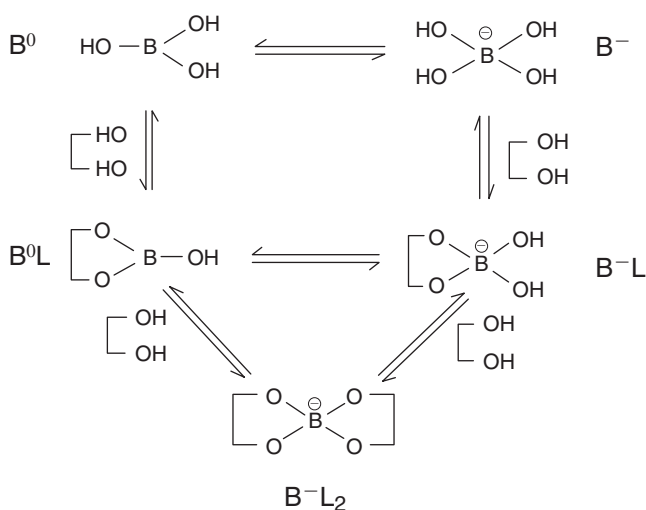
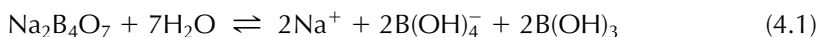
Pectins are used as gelling agents particularly in the food industry in the production of jams and preserves and fruit preparations.

### 4.3.2 Anion-mediated gelation

#### 4.3.2.1 Borate cross-linked polyols

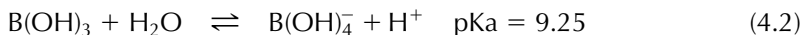
The ability of borax to induce certain polyols, notably PVA and mannose-containing polysaccharides such as guar gum, to form gels has been known as early as the last century [8, 42–44]. Guar gum-borate is used in tertiary oil recovery, while PVA-borate is commonly used as an adhesive and it is sold as a plaything referred to as ‘slime’ for children.

The borate acts by cross-linking the polymer chains and the gels formed are typically described as reversible or ‘self-healing’ gels. Gelation occurs spontaneously on mixing solutions of the polymer and borate. The cross-links are transient with a short lifetime and are continually formed and broken. They are sensitive to temperature, pH, ionic strength and the solvent properties. Cross-linking is assumed to proceed through the monoborate anion, although alternative mechanisms in which boric acid is the reactive species may also be important [43, 44]. Both mechanisms are illustrated in Figure 4.15. In aqueous solution, disodium tetraborate dissociates totally to sodium ions, monoborate ions and free molecular boric acid, according to equation (4.1):



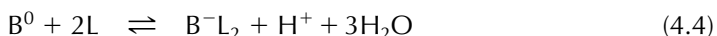
**Figure 4.15** Proposed reaction mechanisms for borate–diol complexation (from Ref. [42]).

The monoborate anion and boric acid are inter-convertible; the equilibrium between them may be expressed (Greenwood, 1973) as:



and equation (4.2) demonstrates the Lewis acidity of orthoboric acid in accepting  $\text{OH}^-$ . The acidity may be dramatically increased by chelation of the monoborate ion, such that the  $\text{pK}_a$  can be as low as 5.15 in the presence of mannitol.

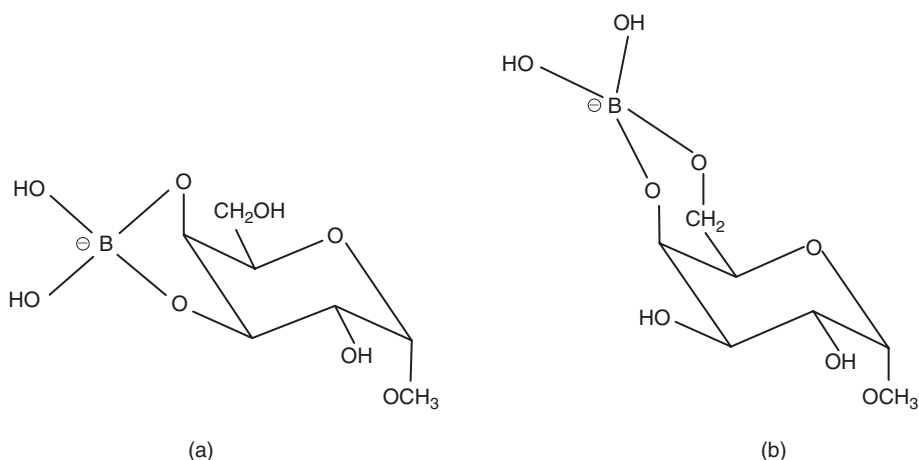
The pH reversibility of borate cross-linked polyols can then be attributed to the pH sensitivity of either equation (4.2) or else the complexation equilibria described below:



where  $\text{B}^0$  = boric acid;  $\text{L}$  = diol and  $\text{B}^-$  = monoborate anion.  $\text{B}^-\text{L}$  may be described as a 1:1 complex and  $\text{B}^-\text{L}_2$  a 2:1 complex.

The structural characteristics of the polyol–borate complexes have been studied by  $^{11}\text{B}$  NMR spectroscopy studies using model diol–borate systems [43].  $^{11}\text{B}$  NMR can distinguish between 1:1 and 2:1 complexes and also between  $\alpha\beta$  and  $\alpha\gamma$  complexes. For the latter two, complexation of *cis*-hydroxyl groups on adjacent carbon atoms is termed  $\alpha\beta$  and results in a 5-membered ring. Reaction with a pair of *cis*-hydroxyls separated by a third carbon atom is termed  $\alpha\gamma$  complexation and results in a 6-membered ring. The two scenarios described above are illustrated in Figure 4.16 [43].

For both guar and PVA the plateau modulus  $G'_p$  has been shown to increase linearly with the borate concentration. At elevated temperatures borate cross-linking is disrupted resulting in a decrease in  $G'$ .



**Figure 4.16** Representation of (a)  $\alpha\beta$  complexation and (b)  $\alpha\gamma$  complexation for methyl  $\alpha$ -D-galactose. Reprinted with permission from [43]. Copyright 1988 American Chemical Society.

## 4.4 Retrogradation

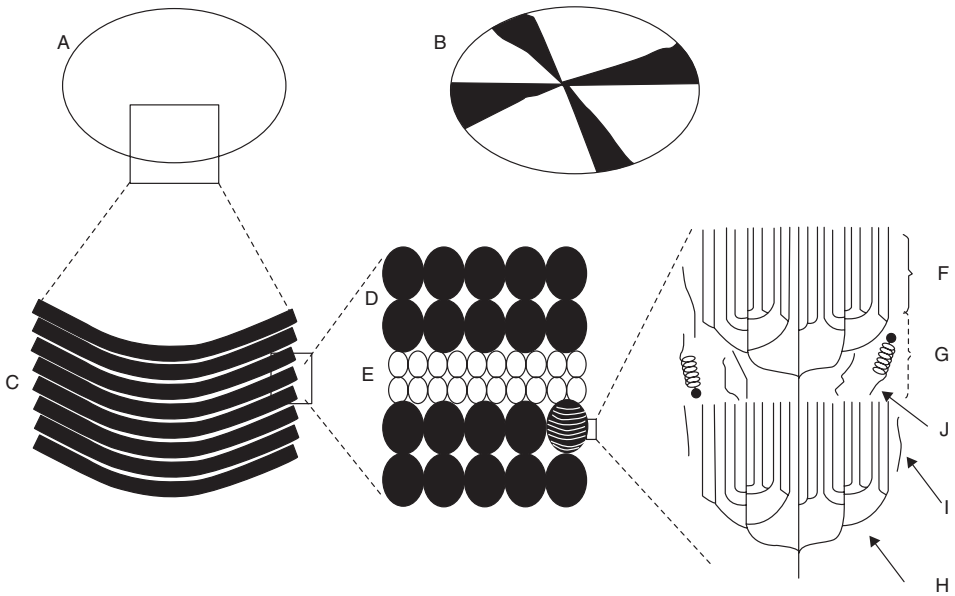
### 4.4.1 Starch

Starch is obtained commercially from cereals (e.g. corn, wheat, rice), roots and tubers (e.g. potato, tapioca) and pulses (e.g. pea), and occurs in the form of granules, which typically vary in size from  $\sim 2\text{--}50\ \mu\text{m}$  as shown in Table 4.2 [45–48]. Starch consists of two polysaccharides, namely amylose and amylopectin and the proportions of each depend on the source (Table 4.2). Amylose consists of linear  $\alpha(1,4)$ -linked glucopyranose chains with very little branching (10 branch points per molecule), while amylopectin also contains sequences of  $\alpha(1,4)$ -linked glucopyranose units, however, it has extensive branching via (1,6) linkages. The molecular mass of amylose may range from  $10^5\text{--}10^6\ \text{g/mol}$  while that for amylopectin may range from  $10^7\text{--}10^8\ \text{g/mol}$ . The crystalline structure of the granule is attributed to the presence of the amylopectin molecules, which arrange themselves in concentric rings [49]. The rings consist of soft amorphous and hard semi-crystalline shells. The latter also consist of a concentric shell structure of alternating amorphous and crystalline lamellae organised into spherical structures termed blocklets which range in diameter from 20–500 nm. A schematic representation of the structure of a starch granule is given in Figure 4.17 [50].

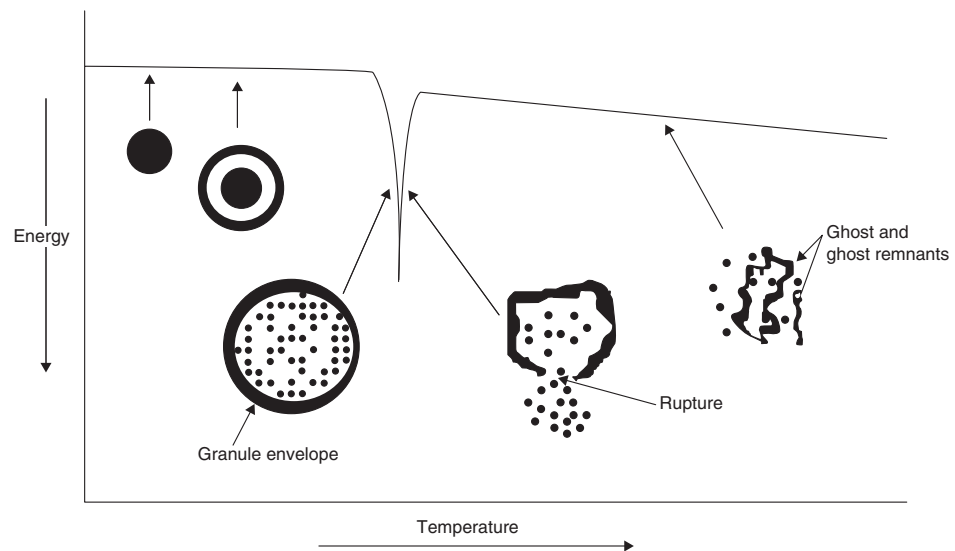
Atkin et al. [51, 52] have shown that in the presence of excess water, water molecules enter the granules and occupy the space between the granular rings and radial expansion occurs increasing the granule volume six-fold. In the case of waxy maize starch ( $\sim 100\%$  amylopectin) blocklets of amylopectin, 200–400 nm in length and 60 nm wide, were observed by transmission electron microscopy. On heating, radial and tangential expansion occurs. The granules may swell up to 25 times their size and the surface develops a translucent envelope, which at a critical stress point ruptures and collapses, releasing amylose molecules into solution. The remaining surface structure degrades to a web-like network referred to as ‘ghosts’. Prior to rupture the amylopectin blocklets in the rings separate and have been shown to exist as 400 nm spherical particles by light microscopy for a range of starch types. The actual temperature at which the granules burst is very characteristic of the source of the starch (see Table 4.2) and is referred to as the gelatinisation temperature. The process can be conveniently followed by DSC which yields an endothermic peak on heating on gelatinisation (Figure 4.18) [51]. On cooling, the amylose molecules self-associate (this process occurs in minutes to hours), a process known as retrogradation,

**Table 4.2** Granule size, amylose content and gelatinisation temperature of various starches

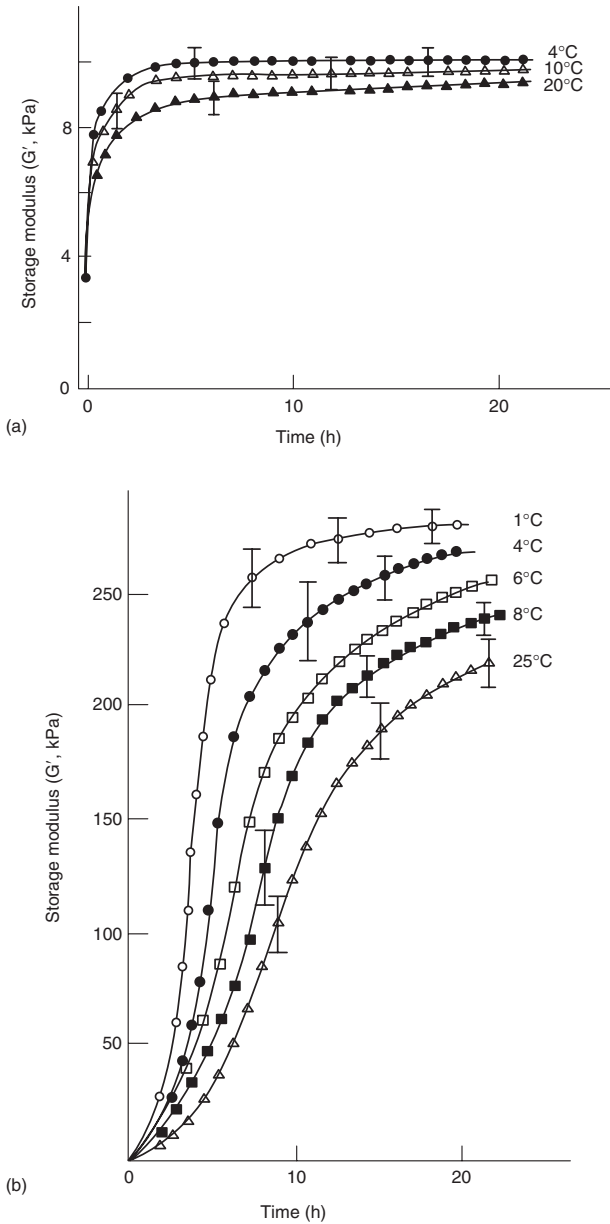
Starch type	Granule size ( $\mu\text{m}$ )	Amylose content (%)	Gelatinisation temperature ( $^{\circ}\text{C}$ )
Corn	2–5	28	67
Waxy corn		98	71
Wheat	2–38	26–28	54
Tapioca	5–35	17	64
Potato	15–100	23	62
Smooth pea	5–10	33–35	
Wrinkled pea	30–40	63–75	



**Figure 4.17** Representation of the structure of a starch granule. The starch granules (A) are birefringent under polarised light (B). The granules exhibit growth rings (C) which consist of alternating hard semi-crystalline (D) and soft amorphous shells (E). The semi-crystalline shell is organised in blocklets composed of stacks of crystalline (F) and amorphous lamellae (G). Amylopectin (H) is responsible for the crystallinity. Amylose (I) and amylose–lipid complexes (J) are not ordered and form amorphous domains (from Ref. [50]).



**Figure 4.18** A representation of the molecular events of gelatinisation coincident with a hypothetical DSC heating curve. Reprinted from [52]. Copyright 1998, with permission from Elsevier.



**Figure 4.19** Storage modulus as a function of time for (a) 5% potato amylose gels at various temperatures and (b) 40% waxy maize amylopectin gels measured at various temperatures. Reproduced with permission from [53].

and a gel is formed. On a longer time-scale (several hours) the amylopectin chains also start to self-associate. The difference in the rates of gelation of amylose and amylopectin are illustrated in Figure 4.19a and 4.19b [53]. Starch gels are usually very turbid and readily undergo syneresis.

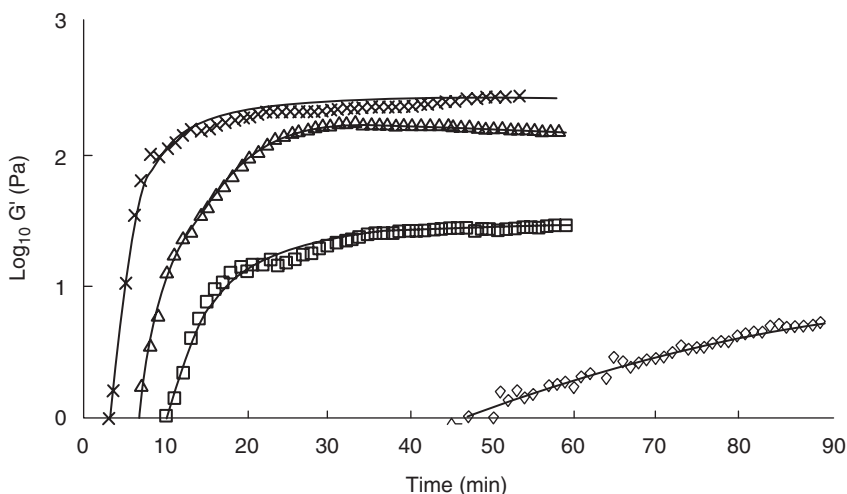
Starch is widely used as a thickener and gelling agent in a broad range of applications including, food, pharmaceuticals, cosmetics, paper manufacture, textiles, etc.

#### 4.4.2 Konjac mannan

Konjac mannan is a glucomannan obtained from the tuber of the konjac plant, notably the *Amorphophallus konjac* species which grows in Southeast Asia particularly Japan, China and Indonesia [54–56]. The tubers are sliced into thin pieces and dried in a hot air drier. They are then pulverised to form particles referred to as konjac flour which can be further purified by washing with ethanol. Konjac mannan is a high molecular mass ( $>10^6$ ) polysaccharide consisting of linear chains of glucose and mannose units linked  $\beta$  (1,4). The main chain has branches, approximately every 10 residues, of up to 16 sugar units linked to the C3 position of the glucose and mannose. The mannose to glucose ratio is 1.6:1 and possible structures of the repeat unit are:



Konjac mannan dissolves in water to form highly viscous solutions. It is acetylated ( $\sim 1$  acetyl group for every 19 sugar residues) and in the presence of alkali, deacetylation occurs and thermally irreversible gels are produced. The rate of gelation is dependent on the polymer and alkali concentration and also on the temperature. This is illustrated in Figure 4.20



**Figure 4.20** Storage modulus of konjac glucomannan solutions at concentrations of 1% (diamonds), 1.5% (squares), 2% (triangles), 3% (crosses), as a function of time at 65°C in the presence of sodium carbonate. Reprinted from [57]. Copyright 1999, with permission from Elsevier.

which shows the increase in storage modulus with time for konjac mannan at varying concentrations in the presence of sodium carbonate at 65°C [57].

Konjac gel has been a popular traditional Japanese food (konnyaku) for over 1000 years. It is also used to produce noodles and jelly dessert. Noodles are produced by pumping an aqueous solution of the konjac mannan through a spinneret immersed in a hot alkaline solution. Gelation occurs yielding 'strings' of konjac gel.

As noted above, konjac mannan modifies the properties of kappa carrageenan gels and interacts with xanthan gum to form thermally reversible gels.

## 4.5 Summary

Polymers are able to form physical gels by association of the polymer chains through hydrogen bonding, hydrophobic interaction and ion cross-linking and may or may not be reversible to temperature. These various mechanisms can be exploited to trigger the gelation process and hence form responsive, intelligent gels.

Polymer gels have a range of mechanical properties from highly elastic (e.g. gelatin) to very brittle (starch) and have extensive industrial application. Novel gel characteristics can be achieved by blending different polymer types incorporating either one or two gelling polymers [58]. In addition 'fluid gels' can be produced by shearing the gelling systems as gelation is occurring. These gels can have a very high low shear viscosity and are able to prevent particle sedimentation very effectively [59].

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## Chapter 5

# Emulsification and Encapsulation

*D. Julian McClements*

### 5.1 Introduction

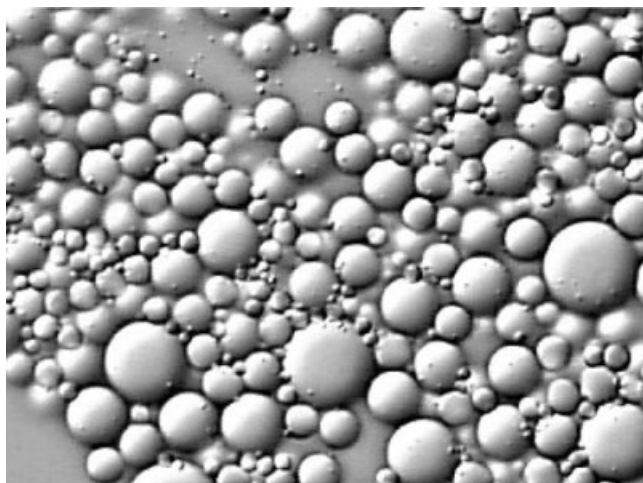
Water soluble polymers are used as emulsifiers in a wide variety of industrial applications, including food, pharmaceutical, health-care, and cosmetic products [1–3]. Emulsifying polymers are normally amphiphilic molecules (i.e. they have both lipophilic and hydrophilic parts) that adsorb to oil–water interfaces and form interfacial membranes around droplets that protect them from aggregation. From a technological point of view it is important to identify the most appropriate polymer that can be used for a particular industrial application, which depends on many factors, including legal constraints, cost, ease-of-utilization, response to environmental conditions, reliability of quality from batch-to-batch, consistency of supply, etc. The purpose of this chapter is to focus on the physicochemical aspects that influence the functionality of water soluble polymers as emulsifiers, and hence influence the choice of an appropriate polymer for forming and stabilizing particular types of oil-in-water emulsions. The chapter will primarily focus upon naturally occurring water soluble polymers commonly used as emulsifiers in the food industry (i.e. amphiphilic proteins and polysaccharides). Nevertheless, most of the material covered in this chapter is also relevant to understanding the functionality of other kinds of amphiphilic polymers.

Initially, this chapter will begin with a description of the major factors influencing the formation, physicochemical properties, and stability of oil-in-water emulsions, as this will facilitate the understanding of the influence of water soluble polymers on emulsion characteristics. The physicochemical basis of the surface activity and film forming properties of water soluble polymers will then be covered. Finally, the characteristics of some of the most important water soluble polymers used as emulsifiers in the food industry will be discussed.

### 5.2 Emulsions

#### 5.2.1 Introduction

An emulsion can be defined as a material that consists of small spherical droplets of one liquid dispersed in another liquid in which it is at least partly immiscible (Figure 5.1). Typically, the diameters of the droplets in emulsions lie somewhere between 0.1 and 100  $\mu\text{m}$  [2, 3]. It is convenient to classify emulsions according to the relative organization of the oil



**Figure 5.1** Optical microscopy photograph of an oil-in-water emulsion consisting of oil droplets dispersed in an aqueous solution.

and aqueous phases. A system that consists of oil droplets dispersed in an aqueous phase is called an *oil-in-water* or O/W emulsion, whereas a system that consists of water droplets dispersed in an oil phase is called a *water-in-oil* or W/O emulsion. The material within the emulsion droplets is usually referred to as the *dispersed*, internal, or *discontinuous phase*, whereas the material that makes up the surrounding liquid is usually referred to as the *continuous* or *external phase*. It is also possible to prepare multiple emulsions (e.g. oil-in-water-in-oil (O/W/O) or water-in-oil-in-water (W/O/W) type) [4–6]. For example, a W/O/W emulsion consists of water droplets dispersed within larger oil droplets, which are themselves dispersed in an aqueous continuous phase. These *multiple* emulsions may have advantages over traditional emulsions for certain applications (e.g. reduction in oil content, controlled release of an active agent, or isolation of one component from another).

The process of creating an emulsion from two separate immiscible liquids, or of reducing the size of the droplets in a pre-existing emulsion, is called *homogenization*. Industrially, this process is usually carried out by mechanical devices known as *homogenizers*, which subject the liquids to intense mechanical stresses that result in droplet disruption. An emulsion can be formed by homogenizing pure oil and pure water together, but the two phases rapidly separate into a system that consists of a layer of oil (lower density) on top of a layer of water (higher density). Phase separation occurs because droplets tend to collide with each other and merge together. The driving force for the phase separation process is the fact that the contact between oil and water molecules is thermodynamically unfavorable, due to the hydrophobic effect [7]. Because of this, emulsions are considered to be *thermodynamically unstable*. However, it is possible to form emulsions that are *kinetically stable* (metastable) for a reasonable period of time (a few days, weeks, months, or years), by including two different classes of substances, *emulsifiers* and *texture modifiers*. Emulsifiers are *surface-active* molecules that absorb at the surface of droplets that are generated during homogenization. There they form a protective membrane that prevents the hydrophobic water molecules from

coming into direct contact with the hydrophobic lipid molecules thus preventing aggregation. The most commonly used water soluble polymers used as emulsifiers in the food industry are amphiphilic proteins and polysaccharides [3, 8]. The second class of compounds used to improve kinetic stability of emulsions is texture modifiers, which can be classified as thickening agents or gelling agents. Thickening agents increase the viscosity of the continuous phase of emulsions, and they are used to modify emulsion texture and to enhance emulsion stability by retarding the movement of droplets. Gelling agents cause the continuous phase to have semi-solid like characteristics that also prevents the movement of the droplets. The most common water soluble polymers used as texture modifiers in the food industry are hydrocolloids (e.g. xanthan gum, alginate, carrageenan, guar gum, pectin, and gelatin) [3]. The term *stabilizer* is used to refer to any ingredient that can improve the stability of emulsions, and may therefore be either an emulsifier or a texture modifier.

## 5.2.2 Droplet characteristics

Many of the most important physicochemical and functional properties of emulsions are governed by the presence of the droplets that they contain [3]. Knowledge of the characteristics of emulsion droplets is therefore important for understanding and controlling emulsion properties.

### 5.2.2.1 Droplet concentration

The droplet concentration is normally expressed in terms of the *disperse phase volume fraction* ( $\phi$ ), which is equal to the volume of all the emulsion droplets ( $V_D$ ) divided by the total volume of the emulsion ( $V_E$ ):  $\phi = V_D/V_E$ . Nevertheless, it can also be expressed in terms of the disperse phase mass fraction ( $\phi_m$ ), which is equal to the mass of emulsion droplets ( $M_D$ ) divided by the total mass of the emulsion ( $M_E$ ):  $\phi_m = M_D/M_E$ . Simple relationships exist to convert mass fraction to volume fraction or *vice versa* [3]. The droplet concentration may also be presented as a mass percentage ( $\% \phi_m = 100\phi_m$ ) or as a volume percentage ( $\% \phi = 100\phi$ ). It should be noted that the 'effective' volume fraction of the droplets in an emulsion may be larger than the actual volume fraction of the dispersed phase (e.g. oil in an O/W emulsion) due to the presence of the interfacial layer around the droplets.

The droplet concentration can be measured using traditional proximate analysis techniques (e.g. drying, solvent extraction, and density measurements) or by using more sophisticated modern analytical techniques (e.g. light scattering, electrical pulse counting, and ultrasonic spectroscopy).

### 5.2.2.2 Droplet size

The size of the droplets in an emulsion is largely determined by the emulsifier type and concentration, the physicochemical properties of the component phases, and the homogenization conditions used to prepare it [3]. A manufacturer normally specifies a pre-established desirable droplet size distribution for a particular product. If the product does not meet this specification it typically must be reprocessed or even discarded.

An emulsion that contains droplets that all have the same size is referred to as being '*monodisperse*', whereas an emulsion that contains droplets that have a range of different sizes is referred to as being '*polydisperse*'. Monodisperse emulsions are sometimes used in fundamental studies because this facilitates the interpretation of experimental measurements. Nevertheless, most industrial homogenizers produce polydisperse emulsions containing a more or less broad range of particle sizes. The size of the droplets in a monodisperse emulsion can be characterized by a single number, such as the droplet diameter ( $d$ ) or radius ( $r$ ), but additional parameters are needed to characterize the droplets in a polydisperse emulsion. The most thorough way of representing a polydisperse emulsion is to report the full *particle size distribution* (i.e. the fraction of droplets in specified size ranges). Nevertheless, in most situations it is sufficient to simply know the mean size of the emulsion droplets and the width of the distribution. Polydisperse emulsions can be characterized according to the general shape of the particle size distributions as being 'monomodal', 'bimodal', or 'multimodal' depending on whether there are one, two, or more peaks in the distribution. There are a variety of different ways of representing the mean particle size of an emulsion and it is important when using or reporting data to be aware of which one is used [3]. Some of the most commonly used mean droplet sizes include the number-weighted mean diameter ( $d_{10} = \sum n_i d_i / \sum n_i$ ), the surface-weighted mean diameter ( $d_{32} = \sum n_i d_i^3 / \sum n_i d_i^2$ ), and the volume-weighted mean diameter ( $d_{43} = \sum n_i d_i^4 / \sum n_i d_i^3$ ), where  $n_i$  is the number of droplets of diameter  $d_i$ .

A variety of analytical techniques have been developed to measure the size of emulsion droplets (e.g. static light scattering, dynamic light scattering, electrical pulse counting, ultrasonic spectroscopy and nuclear magnetic resonance (NMR) restricted diffusion measurements) [3].

### 5.2.2.3 Droplet charge

The electrical charge of emulsion droplets is usually the result of adsorption of emulsifier molecules that contain ionized or ionizable groups (e.g. ionic surfactants, phospholipids, proteins, and polysaccharides). The magnitude and sign of the electrical charge at the droplet interface largely depends on type and concentration of surface-active molecules present at the interface, as well as pH and ionic composition of the aqueous phase. The electrical properties of a droplet interface are usually characterized by the surface charge density ( $\sigma$ ) and the electrical surface potential ( $\Psi_0$ ). The surface charge density is the amount of electrical charge per unit interfacial area, whereas the surface potential is the free energy required to increase the surface charge density from zero to  $\sigma$ . The surface charge density is governed by the type and concentration of ionizable surface-active molecules adsorbed to the interface, as well as by the characteristics of the solution surrounding the interface (e.g. ion concentration, ion type, and dielectric constant) and the prevailing environmental conditions (e.g. temperature).

The sign and magnitude of the electrical charge on an emulsion droplet determines how it interacts with other charged species (e.g. polymers, mineral ions, and other droplets). Charged species of opposite sign are attracted towards each other, whereas those of similar sign are repelled from each other. All of the droplets in an emulsion are usually coated with the same type of emulsifier and so they have the same electrical charge (if the emulsifier is ionized). When this charge is sufficiently large, the droplets are prevented from aggregating because of the electrostatic repulsion between them. The properties of

emulsions stabilized by ionized emulsifiers are particularly sensitive to the pH and ionic strength of the aqueous phase. If the pH of the aqueous phase is adjusted so that the emulsifier loses its charge, or if salt is added to 'screen' the electrostatic interactions between the droplets, the repulsive forces may no longer be strong enough to prevent the droplets from aggregating. Droplet aggregation is often undesirable in emulsions because it can lead to an increase in emulsion viscosity and a decrease in creaming stability. Electrostatic interactions also influence the interactions between emulsion droplets and other charged species, such as biopolymers, surfactants, vitamins, antioxidants, and minerals. These interactions often have significant implications for the overall quality of an emulsion product, for example the susceptibility of emulsified lipids to oxidation depends on whether iron ions are attracted to the droplet surface [9].

The electrical charge on an emulsion droplet can be manipulated by choosing emulsifiers with desirable charge characteristics (e.g. sign, magnitude, isoelectric point (IEP)) and controlling the aqueous phase properties (e.g. pH and ionic strength). Consequently, it is possible to control the bulk physicochemical properties of emulsions by manipulating their electrical charge. A variety of analytical techniques have been developed to measure the magnitude and sign of the charge on emulsion droplets, the most commonly used being particle electrophoresis and electroacoustics [3].

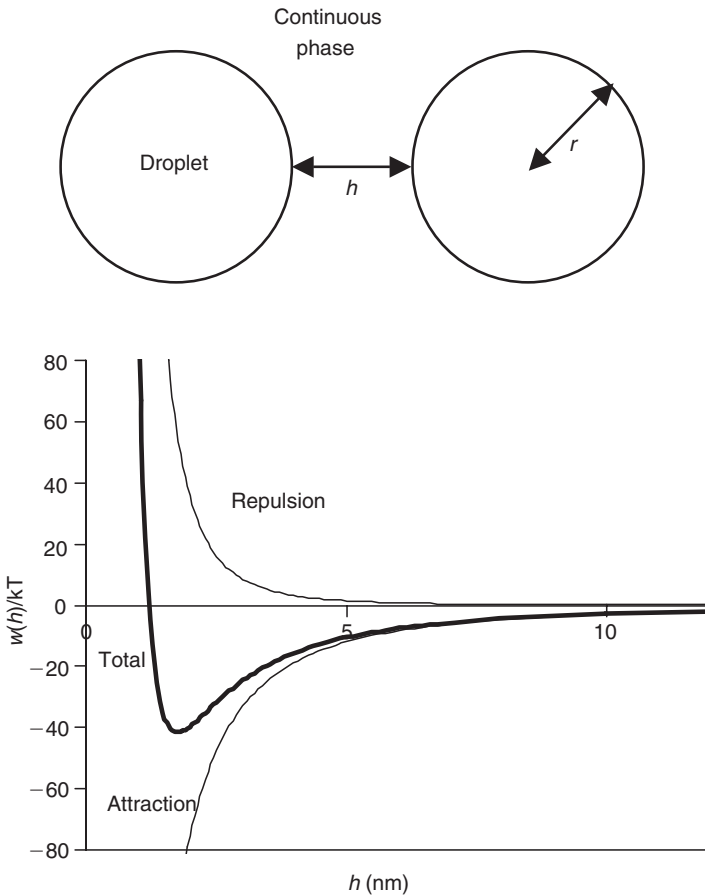
#### 5.2.2.4 *Interfacial properties*

The droplet interface is comprised of a narrow region (typically 2–20 nm thick) that surrounds each emulsion droplet, and contains a mixture of oil, water, and emulsifier molecules. The interfacial region typically does not significantly contribute to the total volume of an emulsion unless the droplet size is smaller than approximately 1  $\mu\text{m}$  [3]. Even so, the interfacial membrane does play a major role in determining bulk physicochemical and functional properties of industrial emulsions. For this reason emulsion scientists are particularly interested in elucidating the factors that determine the composition, structure, thickness, and rheology of the interfacial region [3]. The composition and structure of the interfacial region are determined by the type and concentration of surface-active species present, as well as by the events that occur both during and after emulsion formation (e.g. competitive adsorption, multilayer formation). The thickness and rheology of the interfacial region influences the stability of emulsions to gravitational separation, coalescence and flocculation, and determines the rate at which molecules leave or enter the droplets. A variety of analytical techniques are available to provide information about the composition, thickness, and rheology of interfacial membranes [3]. Some of these techniques can be directly applied to emulsions, whereas others can only be carried out at interfaces separating planar oil–water interfaces.

#### 5.2.2.5 *Droplet interactions*

Colloidal interactions govern whether emulsion droplets aggregate or remain as separate entities thereby impacting the characteristics of any aggregates formed (e.g. their size, shape, porosity, and deformability) [3]. The bulk physicochemical properties and stability of many emulsions depend on the extent of droplet aggregation and the characteristics of any aggregates formed. The interactions between two emulsion droplets can be described

in terms of an *inter-droplet pair potential*. The inter-droplet pair potential,  $w(h)$ , is the energy required to bring two emulsion droplets from an infinite distance apart to a surface-to-surface separation of  $h$  (Figure 5.2). The overall inter-droplet pair potential acting between two droplets is the sum of many different types of interactions, including van der Waals, steric, electrostatic, depletion, hydrophobic, and hydration interactions. These individual interactions can vary in their sign (attractive or repulsive), magnitude (weak to strong), and range (short to long) (Table 5.1). Each of the individual interactions usually has a simple monotonic dependence on surface-to-surface separation, but the sum of the interactions can exhibit fairly complex behavior having both minima and maxima at certain separation distances. Generally, droplets tend to aggregate when attractive interactions dominate, but remain as individual entities when repulsive interactions dominate. It is therefore important to select a water soluble polymer that will generate sufficiently strong repulsion interactions between the droplets under the conditions used.



**Figure 5.2** Colloidal interactions between emulsion droplets are characterized by the change in interaction potential with droplet separation.



**Table 5.1** Summary of major colloidal interactions between emulsion droplets

Type	Sign	Magnitude	Range	Major factors influencing
Van der Waals	A	S	L	Refractive index, dielectric constant
Electrostatic	R or A	W–S	S–L	pH, ionic composition, surface charge
Steric	R	S	S	Solvent quality, thickness, rheology
Depletion	A	W–M	M	Excluded species size and concentration
Hydrophobic	A	S	L	Surface hydrophobicity, temperature

Sign: Attractive (A), Repulsive (R); Magnitude: Weak (W), Medium (M), Strong (S); Range: Short (S), Medium (M), Long (L).

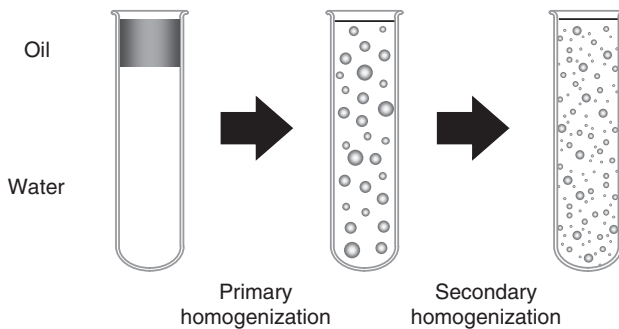
**Table 5.2** Comparison of the attributes of different types of homogenizer used to prepare food emulsions

Homogenizer type	Throughput	Dominant flow regime	Energy density (J/m <sup>3</sup> )	Relative energy efficiency	Minimum droplet size	Sample viscosity
High speed mixer	Batch or continuous	TI, TV, LV	Low–High	Low	2 μm	Low–medium
Colloid mill	Continuous	LV (TV)	Low–High 10 <sup>3</sup> –10 <sup>8</sup>	Intermediate	1 μm	Medium–high
High-pressure homogenizer	Continuous	TI, TV, (CI) LV	Medium–High 10 <sup>6</sup> –10 <sup>8</sup>	High	0.1 μm	Low–medium
Ultrasonic probe	Batch or continuous	CI	Medium–High 10 <sup>6</sup> –10 <sup>8</sup>	Low	0.1 μm	Low–medium
Ultrasonic jet homogenizer	Continuous	CI	Medium–High 10 <sup>6</sup> –10 <sup>8</sup>	High	1 μm	Low–medium
Micro-fluidization	Continuous	TI, TV	Medium–High 10 <sup>6</sup> –2 × 10 <sup>8</sup>	High	<0.1 μm	Low–medium
Membrane processing	Batch or continuous	Injection	Low–Medium <10 <sup>3</sup> –10 <sup>8</sup>	Very High	0.3 μm	Low–medium

TI: Turbulent-Inertial, TV: Turbulent-Viscous, LV: Laminar-Viscous, CI: Cavitational.

5.2.3 Formation of emulsions

The process of converting two immiscible bulk phase liquids into an emulsion, or of reducing the size of the droplets in a pre-existing emulsion, is known as *homogenization*. The mechanical device designed to carry out this process is called a *homogenizer*. The characteristics of some of the most commonly used homogenizers are summarized in Table 5.2. In general, homogenization can be separated into two categories depending on the nature of the starting material. The formation of an emulsion directly from two separate bulk liquids is referred to as *primary* homogenization, whereas the reduction in size of the droplets in an existing emulsion is referred to as *secondary* homogenization (Figure 5.3). The creation of a particular type



**Figure 5.3** Emulsion homogenization may consist of converting a separate oil and water phase into an emulsion (primary homogenization) or breaking up larger droplets into smaller droplets (secondary homogenization).

of emulsion may involve the use of either of these types of homogenization, or a combination of both. In large scale food processing operations it is often more efficient to prepare an emulsion in two stages. First, the separate oil and water phases are converted to a coarse emulsion that contains fairly large droplets using one type of homogenizer (e.g. a high speed blender). The droplets of the emulsion premix, having a low kinetic stability are further reduced in size using a different type of homogenizer (e.g. a high-pressure valve homogenizer). It should be noted that there is no clear distinction between most of the physical processes that occur during primary and secondary homogenization (e.g. mixing, droplet disruption, and droplet coalescence). Finally, some homogenizers are capable of producing emulsions with small droplet sizes directly from separate oil and water phases (e.g. high intensity ultrasonicators, microfluidizers, or membrane homogenizers). Many of the important characteristics of industrial emulsions depend on the size of the droplets they contain, including their stability, texture, appearance, and functionality. Consequently, the major objectives of homogenization is to create an emulsion in which the majority of droplets fall within an optimum size range that yields emulsions with properties specified by the manufacturer. The major factors that determine the size of the droplets produced after homogenization have recently been reviewed, which include emulsifier type and concentration, homogenizer type, homogenization conditions, and physicochemical properties of component phases [3].

#### 5.2.4 Encapsulation of emulsified lipids

A variety of different technologies can be used to convert liquid oil-in-water emulsions into powders containing particles that consist of oil droplets embedded in a solid wall material, including spray drying, freeze drying and roller drying. For sake of clarity, we will focus on spray drying because this is one of the most commonly used methods industrially, being widely used in the food, dietary supplement, cosmetics, personal care, health-care, chemical, and pharmaceutical industries. Spray drying is often used to increase the shelf-life of products, to reduce the amount of product that has to be transported, and/or to increase the convenience of application of the products. Basically, it involves converting a

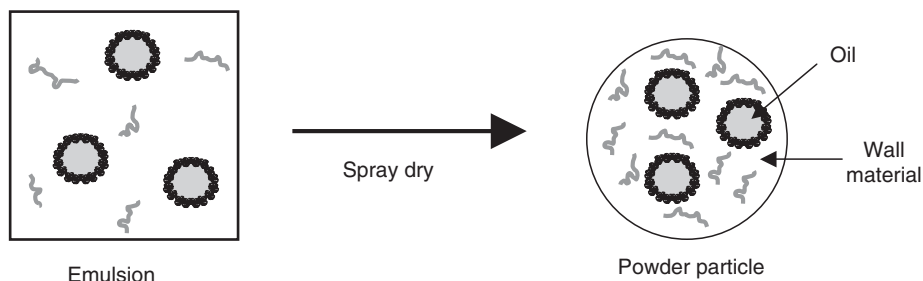
feed material from a fluid state into a powdered state (amorphous or crystalline solid) by spraying it into a hot drying medium (usually air) that evaporates the carrier liquid (usually water) surrounding the particulate matter.

The feed material is pumped through a nozzle that disperses it into small droplets, which are then mixed with the hot drying medium (Figure 5.4). The carrier liquid inside the droplets is evaporated from the droplet surfaces when they come into contact with the drying medium. The fact that evaporation is an endothermic process means that the material within the droplets remains relatively cool during the drying process, which reduces the amount of thermal damage done to any thermally labile components. The spray dryer is designed so that the residence time of the material within it is sufficiently short that it does not heat up considerably. The dried material is then separated from the drying medium and removed from the spray dryer.

A number of economic, physicochemical, and functional characteristics determine the overall quality of a powdered product produced by spray drying, including manufacturing costs, resistance to caking, flow characteristics, bulk density, solubility and dispersion characteristics, shelf-life, appearance and susceptibility to chemical degradation reactions. The efficient production of a high quality spray dried product depends on selection of the most appropriate spray drier design, selection of the most appropriate operating conditions (e.g. input temperature, output temperature, product flow rate, and drying medium flow rate), and selection of the most appropriate feed material composition (e.g. total solids content, wall material type, and viscosity).

Traditionally, spray dried powders are produced from fluid particulate feed materials (such as emulsions, suspensions, or dispersions) by a multi-step process. For the purpose of demonstration, we will consider the spray drying of oil-in-water emulsions (Figure 5.4):

- (1) *Emulsion Formation.* An oil-in-water emulsion is produced by homogenizing an oil phase and an aqueous phase together (see above). This emulsion is usually stabilized by an emulsifier that adsorbs to the oil–water interface, thereby facilitating droplet formation and retarding droplet aggregation. Typically, this emulsifier is either a small molecule surfactant (e.g. lecithin, Tween, Spans, etc) or a biopolymer (e.g. protein, polysaccharide, or protein–polysaccharide complex). In addition, a material that will



**Figure 5.4** Schematic representation of micro-encapsulation of oil droplets in powder particles produced by spray drying. An oil-in-water emulsion containing an appropriate amount of continuous phase materials is dried to form powder particles consisting of oil droplets embedded within a wall material. The wall material often consists of carbohydrates, proteins and/or polar lipids.

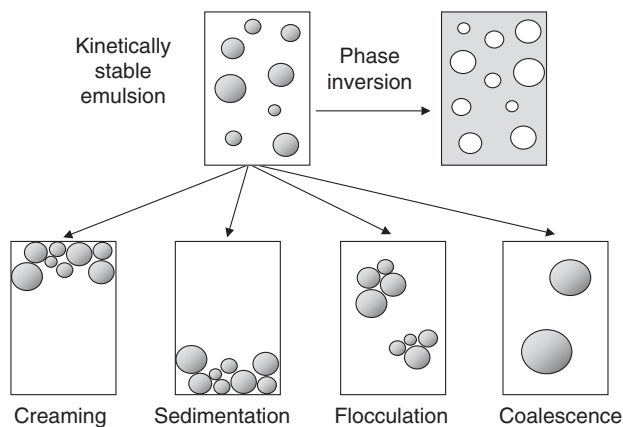
form the walls of the particles in the final powder (the wall material) is also added to the emulsion (e.g. sugar, protein, polysaccharide, or polar lipid).

- (2) *Spray Drying*. The emulsion is used as a feed material for the spray dryer. The emulsion is pumped through a nozzle that disperses it into small droplets. These droplets consist of a number of small oil droplets trapped inside a larger water droplet. The droplets are mixed with the hot drying medium (usually air), which causes most of the water inside them to evaporate, leaving solid like particles consisting of oil droplets embedded in a wall material (which often consists of polar lipids, proteins, and/or carbohydrates).

The quality of the final encapsulated lipid powder depends on a number of factors including, the amount of lipid encapsulated, the fraction of lipid exposed to the environment, the long-term chemical stability of the lipid, the flowability of the powder, the dispersibility of the powder, etc. These parameters can be controlled by selecting appropriate concentrations and types of components to make up the initial emulsion, as well as appropriate operating parameters for the spray dryer (e.g. flow rates, inlet, and outlet temperatures). Water soluble polymers (such as proteins and polysaccharides) are often used as emulsifiers to stabilize oil-in-water emulsions prior to spray drying, and after re-dispersion of the dried powder into liquid. Alternatively, water soluble polymers may make up part of the wall material that helps encapsulate and protect the lipid in the powder during storage.

### 5.2.5 Emulsion stability

Once an emulsion has been created it is important that it retains its desirable properties during storage and application. The term ‘emulsion stability’ is broadly used to describe the ability of an emulsion to resist changes in its properties with time. The properties of an emulsion may evolve over time due to a variety of physical, chemical, or biological processes. From a technological standpoint, it is important to identify the dominant processes occurring in the system of interest because effective strategies can then be rationally designed to overcome the problem. A number of the most important physical mechanisms responsible for the instability of emulsions are shown schematically in Figure 5.5. It is important to have knowledge



**Figure 5.5** Major destabilization mechanisms in oil-in-water emulsions.

of these mechanisms in order to understand how water soluble polymers can influence emulsion stability.

### 5.2.5.1 Gravitational separation

Gravitational separation is one of the most common forms of instability in emulsions and may result in either *creaming* or *sedimentation* depending on the relative densities of the dispersed and continuous phases. Creaming is the upward movement of droplets due to the fact that their density is lower than that of the surrounding liquid, whereas sedimentation is the downwards movement of droplets due to the fact that they have a higher density than the surrounding liquid (Figure 5.5).

The creaming velocity of an isolated rigid spherical particle suspended in a Newtonian liquid obeys Stokes Law:

$$\nu_{\text{Stokes}} = - \frac{2gr^2(\rho_2 - \rho_1)}{9\eta_1} \quad (5.1)$$

where,  $r$  is the radius of the particle,  $g$  is the acceleration due to gravity,  $\rho$  is the density,  $\eta$  is the shear viscosity, and the subscripts 1 and 2 refer to the continuous and dispersed phases, respectively. The sign of  $\nu_{\text{Stokes}}$  determines whether the droplet moves upwards (+) or downwards (−) (i.e. creams or sediments). To a first approximation, the stability of a relatively dilute emulsion to creaming can be estimated using Stokes law. For example, an oil droplet ( $\rho_2 = 910 \text{ kg/m}^3$ ) with a radius of  $1 \mu\text{m}$  suspended in water ( $\eta_1 = 1 \text{ mPa s}$ ,  $\rho_1 = 1000 \text{ kg/m}^3$ ) should theoretically cream at a velocity of about 17 mm per day. An emulsion containing droplets of this size would therefore not have a particularly long shelf-life.

Stokes' Law highlights a number of strategies that industrial manufacturers of emulsions can use to retard gravitational separation (i.e. decreasing the density contrast between the two phases, decreasing the droplet radius, or increasing the viscosity of the continuous phase). Each of these strategies is used in industry, with the most appropriate one or combination of them depending on the nature of the emulsion.

It should be stressed that Stokes' law is inappropriate for accurately predicting gravitational separation in many industrial emulsions because they do not exist as dilute suspensions of non-interacting rigid spheres suspended in a Newtonian fluid. For this reason, the theory has been extended to take into account various other factors, such as droplet fluidity, droplet concentration, particle–particle interactions, and non-Newtonian continuous phases [3].

Water soluble polymers can influence the stability of emulsions to gravitational separation in a variety of ways. Non-adsorbed polymers may either increase or decrease stability depending on their effective size and concentration in solution. Increasing the concentration of a polymer in solution causes an increase in continuous phase viscosity (and may even lead to gelation), which should slow down droplet movement. On the other hand, the presence of non-adsorbed polymer also increases the magnitude of the depletion attraction between droplets, which may cause flocculation and therefore accelerate droplet movement. The presence of an adsorbed polymer may also influence stability to gravitational separation in a number of ways. For example, the size of the droplets produced

during homogenization often depends on the type of polymer used, so that polymers that are more effective at producing small sizes will produce more stable emulsions. In addition, polymers that are more effective at preventing droplet aggregation (see below), and thereby preventing an increase in mean particle size, are also more effective at preventing gravitational separation.

#### 5.2.5.2 Droplet aggregation

The droplets in emulsions frequently encounter their neighbors because they are in continual motion because of the effects of thermal energy, gravity, or applied mechanical forces. After an encounter, emulsion droplets may either move apart or remain aggregated, depending on the relative magnitude of the attractive and repulsive interactions between them [2, 3]. Droplets aggregate when there is a minimum in the inter-droplet pair potential that is sufficiently deep and accessible to the droplets (Figure 5.2). The three major types of aggregation in emulsions are flocculation, coalescence, and partial coalescence.

**Flocculation.** Droplet flocculation is the process whereby two or more droplets come together to form an aggregate in which the droplets retain their individual integrity (Figure 5.5). It may be either advantageous or detrimental to emulsion quality depending on the nature of the product. Flocculation accelerates the rate of gravitational separation in dilute emulsions, which is undesirable because it reduces their shelf-life. It also causes a pronounced increase in emulsion viscosity, and may even lead to the formation of a gel. Some industrial products are expected to have a low viscosity and therefore flocculation is detrimental. In other products, a controlled amount of flocculation may be advantageous because it leads to the creation of a desirable texture. Flocculation may occur in emulsions through a variety of different processes that either increase the attractive forces or decrease the repulsive forces between the droplets, for example, reduction in electrostatic repulsion by changing pH or ionic strength; increase in depletion attraction due to the presence of non-adsorbed polymer; increase in hydrophobic attraction due to an increase in the surface hydrophobicity of the droplets, for example, due to thermal denaturation of adsorbed proteins; adsorption of polymers onto more than one droplet leading to bridge formation [3].

**Coalescence.** Coalescence is the process whereby two or more liquid droplets merge together to form a single larger droplet (Figure 5.5). Coalescence is the principal mechanism by which an emulsion eventually attains its thermodynamically most stable state since the contact area between the oil and water phases decrease in the course of the process [10]. Coalescence also causes emulsion droplets to cream or sediment more rapidly because of the droplet size increase. In oil-in-water emulsions, coalescence eventually leads to the formation of a separate oil layer, a process that is referred to as *oiling off*. In water-in-oil emulsions, it leads to the merging, sedimentation and finally phase separation of water droplets.

Coalescence requires that the molecules of liquid within two or more emulsion droplets coming into direct contact. Droplets therefore need to be in close proximity, which is for example the case in highly concentrated emulsions, flocculated emulsions, or creamed layers. In a subsequent step, a disruption of the interfacial membrane must occur to allow the liquid molecules to come into direct contact. The rate at which coalescence proceeds, and the physical mechanism by which it occurs, is thus highly dependent on the nature of the emulsifier used to stabilize the system. Improving the stability of an emulsion to coalescence may

be achieved by preventing droplet flocculation, preventing formation of a creamed layer, reducing the droplet concentration, and altering the rheological properties of the interfacial membrane to improve rupture resistance.

*Partial coalescence.* Partial coalescence occurs when two or more partially crystalline oil droplets come into contact and form an irregularly shaped aggregate [11]. It is initiated when a fat crystal from one partially crystalline droplet penetrates into the liquid portion of another partially crystallize droplet. Consequently, the lipid crystal is surrounded by lipid molecules instead of water molecules which is thermodynamically favored, that is the fat crystal is better wetted by liquid oil rather than water. Over time the droplets may continue to merge to further reduce the surface area of lipid that is exposed to water. Nevertheless, the aggregates partly retain the shape of droplets from which they were formed due to the low mobility of molecules in fat crystal networks.

Partial coalescence only occurs in emulsions that contain partially crystalline regions. This is because one of the key requirements for partial coalescence is penetration of fat crystals into the liquid phase. If all droplets were completely liquid they would undergo normal coalescence. If all droplets were completely solid they would undergo flocculation rather than partial coalescence because of the lack of liquid lipid regions that had sufficient molecular mobility required for merging. Thus one can expect an 'optimum' crystal content at which partial coalescence would be highest. Indeed it has been found that increasing the solid content of the droplets causes an initial increase in the partial coalescence rate until a maximum value is reached, after which the partial coalescence rate decreases [11]. The solid content at which this maximum rate occurs depends on the morphology and location of the crystals within the droplets, as well as the magnitude of the applied shear stresses.

Water soluble polymers can influence the stability of emulsions to droplet aggregation in a variety of ways. First, adsorbed polymers that are more effective at producing highly-charged and thick interfaces are more likely to increase the repulsive interactions between droplets, thereby preventing flocculation. Second, adsorbed polymers that are capable of producing highly viscoelastic interfaces that are resistant to deformation are more likely to prevent coalescence and partial coalescence. Third, non-adsorbed polymers that are capable of thickening or gelling the continuous phase may prevent droplets from coming into close contact for extended periods by slowing down their movement, hence reducing the likelihood of flocculation or coalescence. Fourth, non-adsorbed polymers may increase the osmotic attraction between droplets, thereby promoting depletion flocculation. Fifth, polymers with an opposite charge to the droplet surfaces may induce bridging flocculation.

### 5.2.5.3 Ostwald ripening

Ostwald ripening is the process whereby large droplets grow at the expense of smaller ones because of diffusion of dispersed phase molecules from one droplet to another through the intervening continuous phase [12]. The origin of this effect is the fact that the solubility of solute molecules within a spherical particle in the surrounding solvent increases as the size of the particle decreases. This leads to a thermodynamic driving force that favors movement of solute molecules from small to large droplets, leading to a net increase in mean droplet diameter with time. The rate of droplet growth is mainly determined by the solubility of the solute molecules in the continuous phase, and is usually only important in systems where the solute has an appreciable solubility. Polymers may retard droplet coalescence by

forming interfaces that are resistant to compression or expansion and that therefore provide a mechanical resistance to droplet shrinkage or growth.

#### 5.2.5.4 Phase inversion

Phase inversion is the process whereby a system changes from an oil-in-water emulsion to a water-in-oil emulsion, or *vice versa* (Figure 5.5). Phase inversion is an essential step in the manufacture of a number of important industrial products, including butter and margarine. On the other hand, phase inversion is undesirable in other products because it has an adverse effect on the products appearance, texture, or stability (e.g. coagulation of cream).

Phase inversion can be triggered by some alteration in the composition or environmental conditions of an emulsion (e.g. disperse phase volume fraction, emulsifier type, emulsifier concentration, solvent conditions, temperature, or mechanical agitation) [3]. Only certain types of emulsion are capable of undergoing phase inversion, rather than being completely broken down into their component phases. These emulsions are capable of existing in a kinetically stable state after the phase inversion has taken place. It is usually necessary to agitate an emulsion during the phase inversion process, otherwise it will separate into its component phases. The physicochemical basis of phase inversion is believed to be extremely complex, involving aspects of flocculation, coalescence, partial coalescence, and emulsion formation. Polymers may influence the likelihood of phase inversion by reducing the tendency for flocculation, coalescence, or partial coalescence to occur (see above).

### 5.2.6 Bulk physicochemical properties of emulsions

#### 5.2.6.1 Emulsion rheology

*Rheology* is the science that is concerned with the relationship between applied stresses and the deformation and flow of matter [13, 14]. Most rheological tests involve the application of a stress to a material and a measurement of the resulting flow or deformation [15]. The extent of the deformation and flow depends on the physicochemical properties of the material, and can provide valuable information about product properties and functionality. A manufacturer must therefore be able to design and produce a product that has the rheological properties expected by the consumer. Sophisticated and sensitive analytical techniques based on these principles are available for characterizing the rheological behavior of industrial emulsions, and are widely used in industrial, government, and academic laboratories.

The stability of many industrial emulsions depends on the rheological characteristics of the component phases, for example, the creaming of oil droplets depends on the viscosity of the aqueous phase. Information about the rheology of emulsion-based products is used by chemical engineers to design processing operations that depend on the way that a product behaves when it flows through a pipe, is stirred or is packed into containers. Rheological measurements are also used by emulsion scientists as an analytical tool to provide fundamental insights about the structural organization and interactions of the components within emulsions.



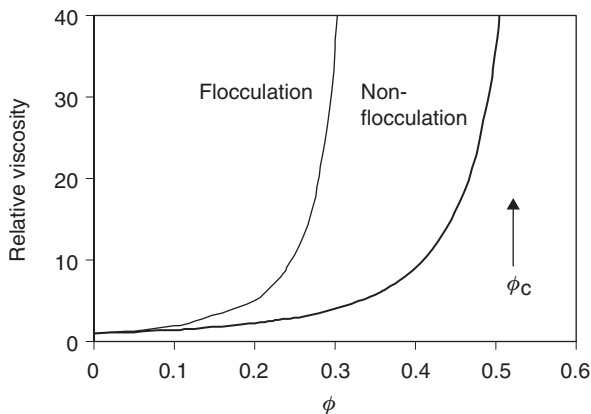
Industrial emulsions are compositionally and structurally complex materials that can exhibit a wide range of different rheological behavior, ranging from low viscosity fluids (such as milk) to solids with relatively high elastic modulus (such as refrigerated butter). Our ability to control the rheological properties of emulsions depends on a quantitative understanding of the relationship between rheology, composition, and microstructure. A variety of theories have been used to relate the rheological properties of emulsions to their composition and microstructure. In general, the apparent viscosity of an emulsion can be described by the following equation [3]:

$$\eta = f(\eta_1, \eta_2, \phi, r, w(h), \tau) \quad (5.2)$$

where  $\eta_1$  is the viscosity of the continuous phase,  $\eta_2$  is the viscosity of the dispersed phase,  $\phi$  is the dispersed phase volume fraction,  $r$  is the droplet radius:  $w(h)$  is the interaction potential between the droplets, and  $\tau$  is the applied shear stress. The precise nature of the equation used to describe the rheological properties of an emulsion depends on the characteristics of the system (e.g. droplet concentration, droplet interactions, and continuous phase rheology). Exact expressions of the relationship between the rheology of colloidal suspensions and their composition/structure are only available in certain limiting cases, such as Einsteins' equation for a dilute suspension of rigid spherical particles:

$$\eta = \eta_1(1 + 2.5\phi) \quad (5.3)$$

This equation illustrates that the rheology of a dilute emulsion is proportional to the rheology of the continuous phase and increases with increasing droplet concentration. The Einstein equation can be extended to account for the effects of droplet fluidity, particle-particle interactions, droplet flocculation, and non-Newtonian continuous phase rheology [3]. A typical plot of the dependence of emulsion viscosity on droplet concentration is shown in Figure 5.6 for non-flocculated and flocculated emulsions. In non-flocculated emulsions, the viscosity increases gradually as the droplet concentration increases until a critical droplet concentration ( $\phi_c$ ) is reached where the droplets become close packed and then the viscosity increases steeply. Emulsions that have droplet concentrations appreciably higher than  $\phi_c$  tend to exhibit viscoplastic type rheological behavior (e.g. mayonnaise). In

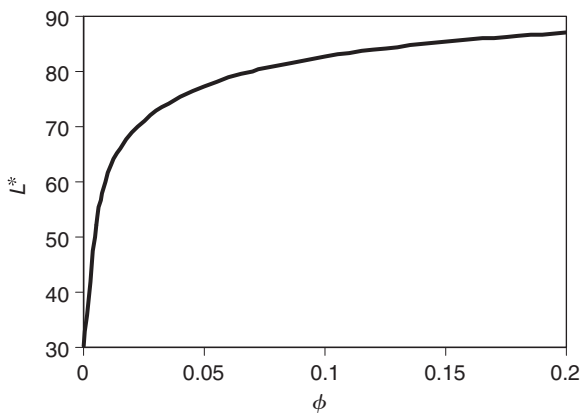


**Figure 5.6** Dependence of emulsion viscosity on droplet concentration for non-flocculated and flocculated emulsions. The viscosity increases with increasing droplet concentration.

flocculated emulsions, the droplet concentration where a sudden increase in viscosity occurs is much lower because network formation occurs. In addition, the viscosity of flocculated emulsions is much higher than that of non-flocculated emulsions because the effective volume fraction of the particles is larger. It should also be noted that many industrial emulsions show highly shear thinning rheological behavior, particularly if they contain non-adsorbed hydrocolloids in the continuous phase or if the droplets are flocculated [3].

#### 5.2.6.2 Emulsion appearance

The optical properties of many industrial emulsions play an important role in determining their quality as it is usually the first sensory impression that a consumer makes of a product [3, 16]. It is therefore often important to understand the factors that determine emulsion appearance as this would aid in the design of emulsion-based products with improved quality. When a light beam is incident upon the surface of an emulsion a portion of the incident light beam is transmitted through the emulsion while another portion is reflected. The relative proportions of light transmitted and reflected at different wavelengths depend on the scattering and adsorption of the light wave by the emulsion. Light scattering and absorption depend on size, concentration, refractive index, and spatial distribution of droplets, as well as the presence of any chromophoric materials (e.g. dyes). Hence, the overall appearance of an emulsion is influenced by its structure and composition. Scattering is largely responsible for the 'turbidity', 'opacity', or 'lightness' of an emulsion, whereas absorption is largely responsible for 'chromaticity' (blueness, greenness, redness, etc). It should be stressed that the overall appearance of an emulsion also depends on the nature of the light source and detector used [17]. Mathematical models have recently been developed to predict the color of emulsions from knowledge of their droplet characteristics [3]. For example, the tristimulus coordinates ( $L$ ,  $a$ ,  $b$  values) of emulsions can be predicted from knowledge of their droplet size, droplet concentration, dye type, and dye concentration. Theoretical predictions and experimental measurements indicate that the 'lightness' of an emulsion increases and the 'color intensity' decreases with increasing droplet concentration (particularly between 0% and 5% droplets), which is due to increased light scattering (Figure 5.7). This



**Figure 5.7** Dependence of 'lightness' ( $L$ -value) on droplet concentration for a typical oil-in-water emulsion. The lightness increases with increasing droplet concentration because of light scattering.

has important implications for the development of reduced fat products, since reducing the concentration of oil droplets in an O/W emulsion below a certain level causes an appreciable change in product appearance.

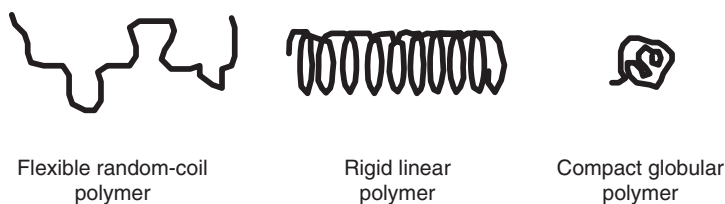
## 5.3 Water soluble polymer emulsifiers

### 5.3.1 Introduction

The term 'emulsifier' is used to describe any surface-active substance that is capable of adsorbing to an oil–water interface and protecting emulsion droplets from aggregation [3]. A number of water soluble polymers have some amphiphilic character and are therefore capable of stabilizing emulsions. The most commonly used water soluble polymer emulsifiers in the food industry are amphiphilic proteins and polysaccharides. These emulsifiers vary widely in their ability to form and stabilize emulsions depending on their molecular and physicochemical characteristics. Ideally, an emulsifier should rapidly adsorb to the oil–water interface during homogenization, reduce the interfacial tension by an appreciable amount, and prevent droplet coalescence from occurring during homogenization [11]. In addition, it is usually important that the emulsifier forms an interfacial membrane that prevents droplet aggregation under the environmental conditions that the product experiences during manufacture, transport, storage, and utilization. In this section, we will review the major types of water soluble polymer emulsifiers used in food products, and discuss some of the factors that should be considered in selecting an emulsifier for a particular application.

### 5.3.2 Molecular characteristics

The ability of water soluble polymers to form and stabilize emulsions are ultimately determined by molecular characteristics such as the type, number, distribution, and bonding of the monomers along the backbone [11, 18, 19]. Usually water soluble polymers used as emulsifiers must have a significant fraction of non-polar monomers so that they can adsorb to an oil–water interface, but not too many or else they will no longer be soluble in water. Surface-active proteins tend to have a significant fraction of non-polar amino acids along their chains, whereas surface-active polysaccharides tend to have non-polar chains or proteins covalently attached to their backbone [18, 20, 21]. The configurations that natural polymer chains tend to adopt in aqueous solutions depend on polymer–polymer and polymer–solvent interactions and can be conveniently divided into three categories: globular, rod-like, or random coil (Figure 5.8). Globular polymers have fairly rigid compact structures, rod-like polymers have fairly rigid extended structures (often helical), and random-coil polymers have highly dynamic and flexible structures. In practice, many natural polymers do not have exclusively one type of conformation, but have some regions that are random coil, some that are rod-like, and some that are globular. Polymers in solution may be present as individual molecules or they may be present as supra-molecular structures where they are associated with one or more molecules of the same or different kind.



**Figure 5.8** Schematic representation of some typical polymers that can be used as emulsifiers.

Finally, it should be mentioned that polymers may undergo transitions from one conformation to another, or from one aggregation state to another, if their environment is altered (e.g. pH, ionic strength, solvent composition, or temperature). The conformation and aggregation state of polymers play a major role in determining their functional attributes, and so it is usually important that scientists are aware of the molecular characteristics of the polymers present in each particular emulsion.

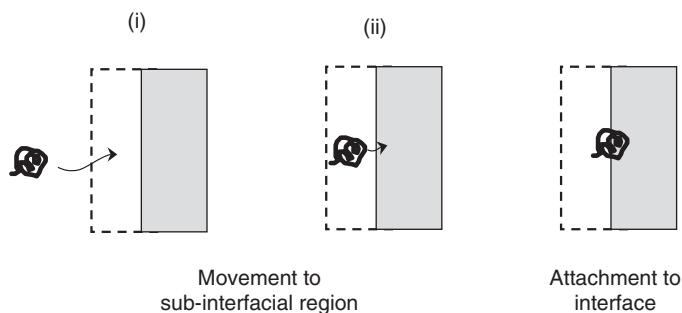
### 5.3.3 *Interfacial activity and emulsion stabilization*

#### 5.3.3.1 *Polymer solvation*

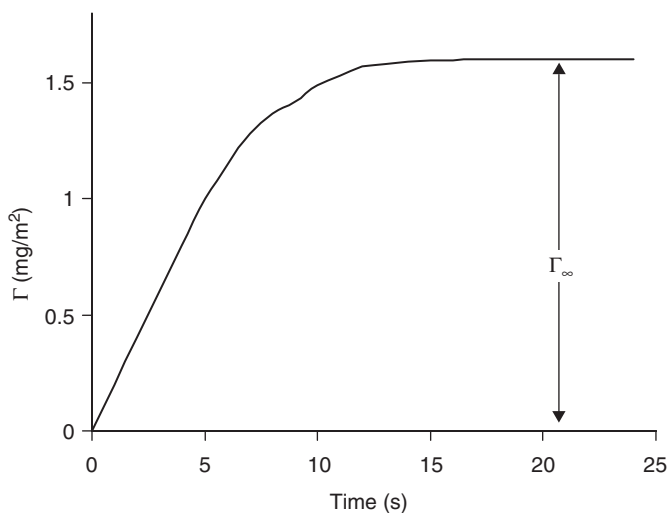
Usually, amphiphilic polymers must be fully dispersed and dissolved in an aqueous solution before they are capable of exhibiting their desirable emulsifying properties [20, 22]. Solvation of polymer ingredients prior to homogenization is therefore an important step in the formation of many industrial emulsions. This process usually involves a number of stages, including dispersion, wetting, swelling, and dissolution. The effectiveness and rate of dissolution depends on many factors, including the nature of the ingredient (e.g. liquid, powder, or granules), polymer type and conformation, pH, ionic strength, temperature, and composition of the aqueous phase, as well as the application of shearing forces. Generally, factors that favor polymer–polymer interactions tend to oppose good dissolution, whereas factors that favor polymer–solvent interactions tend to promote good dissolution. These factors are primarily governed by the nature of the molecular interactions that dominate in the particular system, which depends strongly on polymer type and solvent composition. Discussions of the major factors that influence the dissolution of proteins and polysaccharides are given elsewhere [20–22].

#### 5.3.3.2 *Adsorption kinetics*

The rate at which a polymer adsorbs to an interface is one of the most important factors determining its efficacy as an emulsifier [3, 11, 19]. The adsorption rate depends on the molecular characteristics of the polymer (e.g. size, flexibility, conformation, and interactions), the nature of the bulk liquid (e.g. viscosity, polarity), and the prevailing environmental conditions (e.g. temperature and fluid flow profile). It is often convenient to divide the adsorption process into two stages: (i) movement of the emulsifier molecules from the bulk liquid to the vicinity of the interface, and (ii) attachment of the emulsifier molecules to the interface (Figure 5.9). In practice, emulsifier molecules are often in a dynamic equilibrium between



**Figure 5.9** Adsorption of a polymeric emulsifier to an oil–water interface can be broken down into a number of different steps: (i) movement to the interface; (ii) incorporation into the interface.

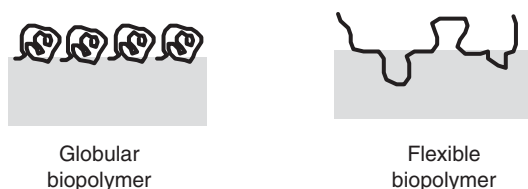


**Figure 5.10** Change in interfacial concentration with time after a polymer solution containing a surface-active polymer is brought into contact with a fresh oil–water interface.

the adsorbed and non-adsorbed states, and so we must also consider the rate at which emulsifier molecules leave the interface when calculating the net adsorption rate. A schematic representation of the change in emulsifier concentration at the interface, expressed as the surface load ( $\Gamma$ ), with time is shown in Figure 5.10. Provided there is sufficient emulsifier present, the interfacial concentration increases with time until it is completely saturated with emulsifier.

### 5.3.3.3 Interfacial activity

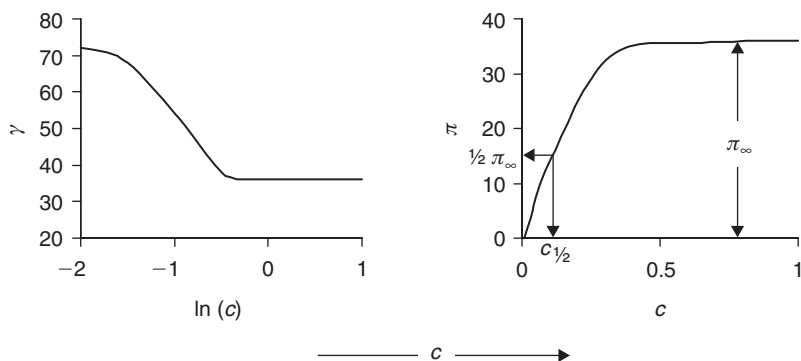
After a polymer ingredient has been adequately dissolved in the aqueous phase it is important to ensure that the solution and environmental conditions (e.g. pH, ionic strength, temperature, and solvent composition) will not promote droplet aggregation during



**Figure 5.11** Schematic representation of conformation of random-coil- and globular polymers at interfaces.

homogenization or after the emulsion is formed. For example, it is difficult to produce protein-stabilized emulsions at pH values close to the IEP of the proteins or at high salt concentrations, because the electrostatic repulsion between the droplets is insufficient to prevent droplet aggregation once the emulsions are formed.

The interfacial activity of many natural polymers is due to the fact that they have both hydrophilic and lipophilic regions distributed along their backbones. For example, most proteins have significant numbers of exposed non-polar amino acid side-groups [20], whereas some polysaccharides have non-polar side chains attached to their polar backbones [23]. The major driving force for adsorption of these amphiphilic biopolymers to oil–water interfaces is therefore the hydrophobic effect. When the polymer is dispersed in an aqueous phase some of the non-polar groups are in contact with water, which is thermodynamically unfavorable because of hydrophobic interactions. When a polymer adsorbs to an interface it can adopt a conformation where the non-polar groups are located in the oil phase (away from the water) and the hydrophilic groups are located in the aqueous phase (in contact with the water). Adsorption also reduces the contact area between the oil and water molecules at the oil–water interface, which lowers the interfacial tension (Figure 5.9). Both of these factors favor the adsorption of amphiphilic biopolymers to oil–water interfaces. The conformation a biopolymer adopts at an interface and the physicochemical properties of the membrane formed depend on its molecular structure and interactions [19]. Flexible random-coil polymers adopt an arrangement where the predominantly non-polar segments protrude into the oil phase, the predominantly polar segments protrude into the aqueous phase and the neutral regions lie flat against the interface (Figure 5.11). The membranes formed by these types of molecules tend to be relatively open, thick, and of low viscoelasticity. Globular polymers (usually proteins) adsorb to an interface so that the predominantly non-polar regions on the surface of the molecule face the oil phase, while the predominantly polar regions face the aqueous phase, and so they tend to have a particular orientation at an interface (Figure 5.11). Once they have adsorbed to an interface, polymers often undergo structural rearrangements so that they can maximize the number of contacts between non-polar groups and oil [19]. Random-coil polymers are relatively flexible molecules and can therefore rearrange their structures fairly rapidly, whereas globular polymers are more rigid molecules and therefore rearrange more slowly. The unfolding of a globular protein at an interface often exposes amino acids that were originally located in the hydrophobic interior of the molecule, which can lead to enhanced interactions with neighboring protein molecules through hydrophobic attraction or disulfide bond formation [24–26]. Consequently, globular proteins tend to form relatively thin and compact membranes that have high viscoelasticities [27]. This may account for the fact that membranes formed by globular proteins are more resistant to rupture than those formed by more random-coil proteins.



**Figure 5.12** The interfacial properties of an emulsifier can be conveniently characterized in terms of the surface tension or surface pressure versus emulsifier concentration in the continuous phase.

The interfacial characteristics of an emulsifier can be described by plotting the surface tension or pressure versus emulsifier concentration (Figure 5.12). The surface pressure is the reduction of the interfacial tension caused by the presence of the emulsifier:  $\pi = \gamma_{o/w} - \gamma$ , where  $\gamma_{o/w}$  is the interfacial tension of a pure oil–water interface, and  $\gamma$  is the interfacial tension in the presence of the emulsifier. The surface tension decreases when an emulsifier is added because the free energy required to increase the surface area by a unit amount is decreased. On the molecular level, this is because the emulsifier reduces the contact area between the oil and water molecules at the interface. The interfacial characteristics of an emulsifier can be conveniently described in terms of three thermodynamic parameters that can be determined from these curves (Figure 5.12):

- **Surface Activity.** The surface activity of an emulsifier can be defined as the reciprocal of the emulsifier concentration where the surface pressure is equal to half its value at saturation ( $\Pi = \frac{1}{2}\Pi_{\infty}$ ):  $1/c_{1/2}$ . The higher the surface activity, the stronger the emulsifiers affinity for the droplet surface.
- **Saturation Surface Pressure.** The surface pressure of the interface when it is saturated with emulsifier molecules ( $\Pi_{\infty}$ ) is determined by how efficient the emulsifier molecules are at minimizing the thermodynamically unfavorable contacts at the interface. It therefore depends on the packing of the emulsifier molecules at the interface, as well as their interactions with the other molecules present there, (e.g. oil and water).
- **Saturation Surface Excess Concentration.** The surface excess concentration at the interface when it is saturated with emulsifier ( $\Gamma_{\infty}$ ) is determined by the mass of the individual emulsifier molecules as well as how efficiently they can pack at the interface.

The above parameters are derived assuming that the adsorption–desorption process is reversible and that there are no emulsifier–emulsifier interactions in the bulk solution or at the interface. In practice, a thermodynamic interpretation of these parameters may therefore be invalid for many real systems because these assumptions are not met. Nevertheless, these parameters still provide a useful means of characterizing and comparing the interfacial properties of emulsifiers in terms of experimentally measurable quantities.

### 5.3.3.4 Emulsion stabilization

To be effective emulsifiers, polymers must rapidly adsorb to the surface of the emulsion droplets created during homogenization, and then form an interfacial membrane that prevents the droplets from aggregating with one another. The interfacial membranes formed by polymers can stabilize emulsion droplets against aggregation by a variety of different mechanisms, (e.g. steric, electrostatic, and hydration repulsion). The stabilizing mechanism that dominates in a particular system is largely determined by the characteristics of the interfacial membrane formed (e.g. thickness, electrical charge, internal packing, exposed reactive groups). The dominant stabilizing mechanism operating in a particular emulsion determines the sensitivity of the system to droplet aggregation under different solution and environmental conditions (e.g. pH, ionic strength, temperature, and solvent quality). In the following sections, we will describe and compare the interfacial properties and emulsion stabilizing abilities of proteins and polysaccharides commonly used as food emulsifiers.

## 5.4 Selection of an appropriate polymeric emulsifier

In this section, we will discuss some schemes for comparing the effectiveness of different types of polymeric emulsifier, as well as some of the factors that should be considered when selecting an emulsifier for a particular application. As has been mentioned earlier an effective emulsifier should have the following general characteristics: (i) it should be capable of rapidly adsorbing to the surface of freshly formed droplets during homogenization; (ii) it should be capable of reducing the interfacial tension by a significant amount; (iii) it should be capable of forming an interfacial membrane that is either resistant to rupture and/or provides a sufficiently strong repulsive interaction between the droplets. There are many different types of water soluble polymers that exhibit these general characteristics and so can be used as emulsifiers. Nevertheless, they vary considerably in their ability to form and stabilize emulsions, as well as in their sensitivity to environmental conditions (e.g. pH, ionic strength, temperature, and solvent composition). It is therefore useful to have a standardized means of assessing the relative efficiency of different types of emulsifiers for specific applications. There has been little attempt to systematically compare the advantages and disadvantages of different emulsifiers under standardized conditions, so that it is currently difficult for emulsion manufacturers to rationally select the most suitable emulsifier for particular products. One of the purposes of this section is therefore to highlight some criteria that could form the basis for such a comparison.

Manufacturers of emulsion-based products usually measure and compare the functional properties of emulsifiers in terms of parameters that depend on the processing procedure and formulation of their actual product, for example:

- The minimum droplet size ( $d_{\min}$ ) that can be produced by a certain amount of emulsifier for a specified emulsion system using specified homogenization conditions.
- The minimum amount of the emulsifier ( $c_{\min}$ ) required to produce a desired droplet size for a specified emulsion system using specified homogenization conditions.



- The long-term stability (e.g. to creaming, flocculation, or coalescence) of a specified emulsion system produced by an emulsifier using specified homogenization conditions.

The characteristics of the specified emulsion system (e.g. oil type, oil concentration, and aqueous phase composition) used to establish the efficiency of an emulsifier depends on the product being produced, and will vary considerably from product-to-product. In addition, the specified homogenization conditions will also depend on the type of homogenizer used (e.g. high speed blender, high-pressure valve homogenizer, microfluidizer, or colloid mill) and the precise operating conditions (e.g. energy input, flow rate, and temperature). The above approach is particularly suited for manufacturers trying to determine the best emulsifier for utilization in their specific product, but it is not particularly suited for development of a general classification scheme because of the wide variation in the composition and processing of different emulsion-based products. This approach could be used to develop a more general classification scheme by stipulating standardized emulsion systems and homogenization conditions.

More quantitative analytical protocols have been developed that attempt to compare the ability of emulsifiers to form and stabilize emulsions (e.g. *emulsifier capacity* (EC) and *emulsion stability index* (ESI)) [3]. The EC of an emulsifier is defined as the maximum amount of oil that can be dispersed in an aqueous solution containing a specific amount of the emulsifier without the emulsion breaking down or inverting into a water-in-oil emulsion [28]. The ESI provides a measure of an emulsifier's effectiveness at producing emulsions that remain stable to droplet aggregation under specified conditions. It is usually determined by measuring the change in particle size of an emulsion after storage for a specified length of time or after exposure to a specific environmental stress (e.g. heating, freezing, and stirring). There are a number of limitations associated with both of these methods that have recently been reviewed [3].

Other quantitative physical parameters that can be determined using fundamental analytical instruments under well-defined environmental conditions can be used to characterize and compare emulsifier properties:

- *Surface Load*,  $\Gamma_{\infty}$ . The surface load at saturation is the mass of emulsifier adsorbed per unit surface area of interface when the interface is saturated with emulsifier, and is usually expressed as  $\text{mg/m}^2$ . The surface load provides a measure of the minimum amount of emulsifier required to produce an emulsion with a given surface area (or droplet size): the higher  $\Gamma_{\infty}$ , the greater the amount of emulsifier required to completely cover the same surface area.
- *Maximum Surface Pressure*,  $\pi_{\infty}$ . The maximum surface pressure provides a measure of the ability of an emulsifier to decrease the oil–water interfacial tension, and thereby facilitate droplet disruption: the higher  $\pi_{\text{max}}$ , the lower the Laplace pressure and the smaller the droplets that can be produced in a homogenizer at a fixed energy input, provided there is sufficient emulsifier present and that it adsorbs rapidly to the droplet surfaces.
- *Surface Activity*,  $1/c_{1/2}$ . The surface activity is a measure of how strongly an emulsifier adsorbs to an oil–water interface (see above). The stronger the binding affinity (the higher  $1/c_{1/2}$ ), the lower the concentration of emulsifier required to reach interfacial saturation.
- *Adsorption Kinetics*,  $\tau_{\text{ads}}$ . Adsorption kinetics can be defined in terms of the average time required for an interface to become saturated with emulsifier. It is important that this

time be measured under conditions that adequately represent the highly dynamic conditions that occur in most homogenizers. In practice, it is difficult to establish an accurate measure of the adsorption kinetics of different emulsifiers under realistically dynamic conditions.

- **Droplet Aggregation Stability.** The aggregation stability is a measure of the tendency for droplets to become aggregated (flocculated or coalesced) under a specified set of environmental conditions (e.g. pH, ionic strength, temperature, and shearing rate). It can be expressed in a number of different ways, for example, the percentage of droplets that are flocculated or coalesced, the percentage of droplets larger than a specified size, or the percentage increase in the mean size of the particles in an emulsion due to droplet aggregation.

Usually, proteins have higher surface activities, lower surface loads, higher maximum surface pressures, and faster adsorption kinetics than polysaccharides, and so they can be used to make emulsions with smaller droplets using less mass of emulsifier. On the other hand, polysaccharide emulsifiers tend to make emulsions that have better stability to environmental stresses (pH, ionic strength, and temperature) than protein emulsifiers, because the interfacial membranes are thicker and more resistant to rupture.

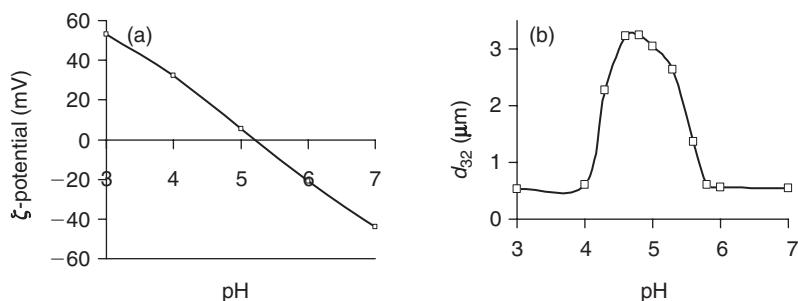
In addition to the physicochemical characteristics considered above, a manufacturer must also consider a number of economic, legal, and marketing factors when selecting a suitable polymeric emulsifier.

## 5.5 Common water soluble polymers used as emulsifiers in foods

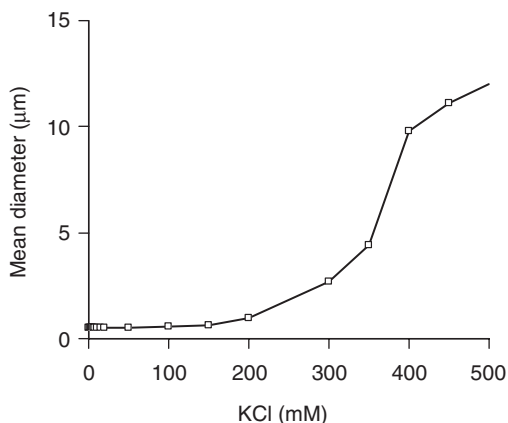
Many food emulsions are stabilized by surface-active polymers that adsorb to droplet surfaces and form protective membranes. Some of these functional polymers are integral components of more complex food ingredients used in food manufacture (e.g. milk, eggs, meat, fish, and flour), whereas others have been isolated from their normal environments and possibly modified before being sold as specialty ingredients (e.g. protein concentrates or isolates, hydrocolloid emulsifiers). In this section, we will focus primarily on those surface-active polymers that are sold as functional ingredients specifically designed for use as emulsifiers in foods.

### 5.5.1 Proteins

The interfacial membranes formed by proteins are usually relatively thin and electrically charged, hence the major mechanism preventing droplet flocculation in protein-stabilized emulsions is electrostatic repulsion [29]. Consequently, protein-stabilized emulsions are particularly sensitive to pH and ionic strength effects, and will tend to flocculate at pH values close to the IEP of the adsorbed proteins and when the ionic strength exceeds a certain level (Figures 5.13 and 5.14). Emulsions stabilized by globular proteins are also particularly sensitive to thermal treatments, because these proteins unfold when the temperature exceeds a critical value exposing reactive non-polar and sulfhydryl groups. These reactive groups increase



**Figure 5.13** pH-dependence of (a) the droplet charge and (b) mean particle size for a whey protein-stabilized emulsion. Extensive droplet flocculation occurs in protein-stabilized emulsions near the IEP of the adsorbed proteins, because the electrostatic repulsion between the droplets is not large enough to overcome the attractive interactions.



**Figure 5.14** Salt-dependence of the mean particle size for a whey protein-stabilized emulsion. Extensive droplet flocculation occurs when the KCl concentration exceeds a critical level due to screening of the electrostatic repulsion between the droplets.

the attractive interactions between droplets, which may lead to droplet flocculation. It should be noted that a number of methods have been developed to attempt to improve the emulsifying properties of protein ingredients, including limited hydrolysis to form peptides, modification of protein structure by chemical, physical, enzymatic, or genetic means, and blending of the proteins with other ingredients, although not all of these processes are currently legally allowed.

### 5.5.1.1 Milk proteins

Protein ingredients isolated from bovine milk are widely used as emulsifiers in emulsion-based food products, such as beverages, frozen desserts, ice creams, sports supplements,

infant formula, and salad dressings. Milk proteins can be conveniently divided into two major categories: caseins ( $\sim 80$  wt.%) and whey proteins ( $\sim 20$  wt.%) [30].

Casein consists of four major protein fractions:  $\alpha_{S1}$  ( $\sim 44\%$ ),  $\alpha_{S2}$  ( $\sim 11\%$ ),  $\beta$  ( $\sim 32\%$ ) and  $\kappa$  ( $\sim 11\%$ ) [30]. In general, caseins have relatively random and flexible structures in solution, although they do have a limited amount of secondary and tertiary structure [31]. The caseins also have some regions that are highly non-polar and others that are highly-charged, which plays a major role in determining their molecular and functional properties in foods [32]. Caseinate-stabilized emulsions are unstable to droplet flocculation at pH values (3.5–5.3) close to the protein's IEP and at relatively high ionic strengths [33–41]. Caseinate-stabilized emulsions tend to be more stable to heating than whey protein-stabilized emulsions, presumably because the relatively flexible casein molecules do not undergo appreciable heat-induced conformational changes like globular proteins do [42, 43]. It should be noted that non-adsorbed caseinate can promote depletion flocculation in emulsions if it is present at sufficiently high concentrations [43, 44].

Whey protein is also a complex mixture of different individual proteins, with the most common being  $\beta$ -lactoglobulin ( $\sim 55\%$ ),  $\alpha$ -lactalbumin ( $\sim 24\%$ ), serum albumin ( $\sim 5\%$ ), and immunoglobulins ( $\sim 15\%$ ) [30]. Unlike caseins, the whey proteins are globular proteins that have fairly compact structures. Whey protein-stabilized emulsions tend to flocculate at pH values ( $\sim 4$ –5.5) close to their IEP ( $\sim 5$ ) [45], at high salt concentrations [33, 42, 45–48] and upon heating above the thermal denaturation temperature of the adsorbed proteins in the presence of salt [26, 49–51]. The tendency for droplet flocculation to occur near the IEP of whey protein-stabilized emulsions is illustrated in Figure 5.13, while the tendency for droplet flocculation to occur due to the addition of mineral ions is shown in Figure 5.14. Users of whey protein emulsifiers in the food industry have reported that large variations in their functional properties can occur from batch-to-batch, which has been attributed to the presence of impurities and partial denaturation of the proteins during their isolation.

It should be noted that the composition of milk protein-stabilized emulsions can change substantially after homogenization due to exchange of adsorbed emulsifiers with non-adsorbed emulsifiers. For this reason, a number of workers have studied preferential adsorption and competitive displacement of milk proteins with each other and with other types of emulsifiers [27, 32, 52–58].

### 5.5.1.2 Meat and fish proteins

Meat and fish contain a number of proteins that are surface-active and capable of stabilizing emulsions (e.g. gelatin, myosin, actomyosin, sarcoplasmic proteins, and actin) [59–61]. Many of these proteins play an important role in stabilizing meat emulsions (i.e. products formed by blending or homogenizing fat, meat, and other ingredients). Emulsion stabilization is partly due to their ability to adsorb to the oil–water interface and partly due to their ability to increase the aqueous phase viscosity or to form a gel in the aqueous phase [60]. Gelatin is one of the few proteins that have been isolated from meat and fish and sold commercially as a functional emulsifier ingredient. Gelatin is a relatively high molecular weight protein derived from animal collagen (e.g. pig, cow, or fish). Gelatin is prepared by hydrolyzing collagen by boiling in the presence of acid (Type A gelatin) or alkaline (Type B gelatin). The IEP of Type A gelatin ( $\sim 7$ –9) tends to be higher than that of Type B gelatin

(~5). Gelatin exists as a random-coil molecule at relatively high temperatures, but undergoes a coil-helix transition upon cooling below a critical temperature, which is about 10–25°C for pig and cow gelatin and about 0–5°C for fish gelatin [62]. Gelatin has been shown to be surface-active and capable of acting as an emulsifier in oil-in-water emulsions [63, 64]. Nevertheless, when used on its own gelatin often produces relatively large droplet sizes during homogenization [64, 65], so that it has to be hydrophobically modified by attachment of non-polar side-groups [66] or used in conjunction with anionic surfactants to improve its effectiveness as an emulsifier [63, 67]. Research has been carried out to establish the ability of various other protein fractions of fish and meat muscle to act as emulsifiers [60, 68–71]. The ultimate objective of this work is to be able to convert waste products from fish and meat production into value-added functional ingredients for use as emulsifiers in foods. Nevertheless, there are currently few examples of functional ingredients derived from fish or meat products (other than gelatin) designed especially as emulsifiers.

### 5.5.1.3 *Egg proteins*

Both egg yolk and egg white contain a mixture of protein and non-protein components that are surface-active [72–76]. Egg ingredients can be purchased in a variety of different forms for utilization in foods, including fresh egg yolks, frozen egg yolks, dried egg yolks, fresh whole eggs, frozen whole eggs, and dried whole eggs [77–82]. In the food industry, egg white is more commonly used for stabilizing foams, whereas egg yolk is more commonly used for stabilizing emulsions [74, 75, 81–84]. Nevertheless, a number of studies have shown that egg white proteins can be used to stable oil-in-water emulsions [85, 86]. Egg yolk is widely used as an emulsifier in the production of mayonnaise, salad dressings, sauces, and cake batters [72, 75, 87]. The effectiveness of whole egg yolk and its individual constituents (plasma and granules) at forming oil-in-water emulsions has been investigated [72–74]. Measurements of the mean particle diameter of the emulsions showed that plasma (mainly low density lipoprotein (LDL) and livetin) produced the smallest particles, followed by whole egg yolk, followed by granules (mainly high density lipoprotein (HDL) and phosvitin). Recently it has been demonstrated that LDL is the main contributor to the emulsifying properties of the plasma constituents [74, 88]. The mean particle diameter of emulsions stabilized by egg yolk decreased from pH 3 to 9, suggesting that egg yolk was more efficient at forming emulsions at higher pH values. Studies of the ability of whole egg yolk, plasma, and granules to stabilize oil-in-water emulsions prepared using a high-pressure valve homogenizer have also been carried out [83, 84]. These researchers found that the main contributors to egg yolk functionality as an emulsion stabilizer were the plasma constituents, rather than the granules. Emulsions stabilized by egg yolk were found to be stable to droplet flocculation at pH 3 at relatively low salt concentrations (150 mM NaCl), but unstable to flocculation at pH 3 at high salt concentrations (550 mM NaCl) and at pH 7 (150 and 550 mM NaCl) [87]. The instability of these emulsions was attributed to depletion, bridging, and electrostatic screening effects. It therefore seems that egg yolk is better at forming emulsions at high pH [72, 73], but stabilizing emulsions at low pH [87]. Understanding the influence of pH and salt concentration on the stability of egg yolk-stabilized emulsions is often complicated because these factors influence the solubility and structural organization of the protein molecules, as

well as the interactions between the emulsion droplets [89]. Like other globular proteins, the proteins in eggs will unfold and aggregate upon heating above their thermal denaturation temperature, which influences the stability and rheological properties of emulsions [81–83]. Emulsions stabilized by egg yolk have been shown to have poor stability to freeze-thaw cycling [74]. Preferential adsorption and competitive displacement of egg yolk proteins with each other and with other types of emulsifiers have been reviewed [74].

#### 5.5.1.4 *Plant proteins*

Surface-active proteins can be extracted from a variety of plant sources, including legumes and cereals [60]. A considerable amount of research has been carried out to establish the ability of these proteins to stabilize emulsions, and whether they could be made into commercially viable value-added ingredients for utilization as emulsifiers in foods [90, 91]. One of the most widely studied proteins extracted from a plant source is soy protein, which is commercially available as a protein concentrate or isolate [92–95]. Soy protein ingredients are a complex mixture of many individual protein fractions with different molecular and functional characteristics (e.g. 2S, 7S, 11S, and 15S fractions) [60]. In addition, each of these fractions contains a mixture of different protein sub-units that also have different molecular and functional characteristics.

Previous studies have shown that soy proteins can decrease the interfacial tension between oil and water and therefore facilitate emulsion formation [60]. Researchers have shown that it is possible to form stable oil-in-water emulsions using soy proteins or their fractions as emulsifiers [93, 94]. Nevertheless, compared to the other sources of proteins mentioned earlier, there have been far fewer systematic studies on the influence of environmental conditions (pH, ionic strength, and temperature) on the stability of soy protein-stabilized emulsions. Emulsions prepared using soy protein concentrates or isolates tend to be highly flocculated, possibly because of bridging of the relatively large soy protein aggregates between droplets [60]. Consequently, soy proteins could be used to stabilize emulsions where droplet creaming is not usually a problem, for example, food products with relatively high droplet concentrations or high continuous phase viscosities. On the other hand, soy protein ingredients may be unsuitable for stabilizing relatively dilute emulsions where creaming would be accelerated by droplet flocculation. Nevertheless, researchers are examining methods of improving the emulsifying properties of soy proteins by fractionating them, by physically, chemically, enzymatically, or genetically modifying them [60, 92, 96] or by using them in combination with other ingredients [97].

### 5.5.2 *Polysaccharides*

#### 5.5.2.1 *Gum arabic*

Gum arabic is widely used as an emulsifier in the beverage industry to stabilize cloud and flavor emulsions [98]. It is derived from the natural exudate of *Acacia Senegal*, and consists of at least three high molecular weight biopolymer fractions. The surface-active fraction is believed to consist of branched arabinogalactan blocks attached to a polypeptide

backbone [23]. The hydrophobic polypeptide chain is believed to anchor the molecules to the droplet surface, while the hydrophilic arabinogalactan blocks extend into solution. The interfacial membrane formed by gum arabic is believed to provide stability against droplet aggregation mainly through steric repulsion, but with some contribution from electrostatic repulsion also [99, 100]. The influence of a variety of processing conditions on gum arabic functionality has been examined [101–104]. For example, it has been shown that gum arabic-stabilized emulsions remain stable to droplet flocculation when exposed to a wide range of conditions (e.g. pH (3–9), ionic strength (0–25 mM  $\text{CaCl}_2$ ) and thermal treatment (30–90°C)) [100]. Nevertheless, gum arabic has a relatively low affinity for oil–water interfaces compared to most other surface-active biopolymers, which means that it has to be used at relatively high concentrations to form stable emulsions. For example, as much as 20% gum arabic may be required to produce a stable 12 wt.% oil-in-water emulsion [105]. For this reason, its application as an emulsifier is restricted to products that have relatively low droplet concentrations (e.g. beverage emulsions). In addition, there have been frequent problems associated with obtaining a reliable source of consistently high quality gum arabic that has led many food scientists to investigate alternative sources of biopolymer emulsifiers for use in beverages [98]. Gum arabic has a high water-solubility and a relatively low solution viscosity compared to other gums, which facilitates its application as an emulsifier.

#### 5.5.2.2 *Modified starch*

Natural starches are hydrophilic molecules that have poor surface activity. Nevertheless, they can be made into effective emulsifiers by chemically attaching hydrophobic moieties along their backbones [106]. These modified starches are widely used as emulsifiers in the beverage industry. One of the most commonly used modified starches is an octenyl succinate derivative of waxy-maize [8, 106]. It consists primarily of amylopectin that has been chemically modified to contain a side-group that is anionic and non-polar. These side-groups anchor the molecule to the oil droplet surface, while the hydrophilic starch chains protrude into the aqueous phase and protect droplets against aggregation through steric repulsion. Because the dominant stabilizing mechanism is steric repulsion, emulsions stabilized by modified starch are resistant to changes in pH (3–9), ionic strength (0–25 mM  $\text{CaCl}_2$ ) and temperature (30–90°C) [100]. Like gum arabic, modified starch has a relatively low interfacial activity (compared to proteins or surfactants), and so a large excess must be added to ensure that all the droplet surfaces are adequately coated. For example, it is recommended that about 12% modified starch is required to produce a stable 12 wt.% oil-in-water emulsion [105]. Modified starches usually come in powdered or granular forms that are easily dispersible in cold water.

#### 5.5.2.3 *Modified celluloses*

In its natural state cellulose is not usually suitable for utilization as an emulsifier because it forms strong intermolecular hydrogen bonds, which make it insoluble in water. Nevertheless, it can be isolated and modified in a number of ways to produce food-grade ingredients that have interfacial activity and can be used as emulsifiers [107]. The most commonly used surface-active cellulose derivatives are methyl cellulose (MC), hydroxypropyl cellulose (HPC), and methyl hydroxypropyl cellulose (MHPC). These ingredients

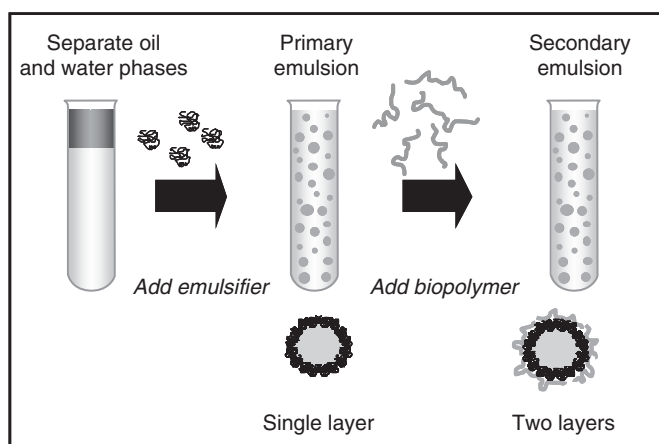
are all non-ionic polymers that are soluble in cold water, but tend to become insoluble when the solution is heated above a critical temperature (around 50–90°C). They have good stability to pH (2–11), salt and freeze-thaw cycling, which may be beneficial in a number of food emulsion applications.

#### 5.5.2.4 Other polysaccharides

A number of studies have shown that various other types of polysaccharide are capable of reducing oil–water interfacial tensions and forming stable emulsions (e.g. galactomannans, pectin, and chitosan) [23, 107–109]. Nevertheless, there is still some debate about the molecular origin of their surface activity (e.g. non-polar regions on the polysaccharide molecule itself, protein contaminants, or protein moieties bound to the polysaccharides), and about whether their ability to form stable emulsions is primarily due to their surface activity or the ability to thicken the aqueous phase [23].

#### 5.5.3 Protein–polysaccharide complexes

Proteins tend to be better at producing small emulsion droplets when used at low concentrations than polysaccharides, whereas polysaccharides tend to be better at producing emulsions that are stable to a wider range of environmental conditions than proteins (e.g. pH, ionic strength, temperature, and freeze-thaw cycling) [3]. It may therefore be advantageous to combine the beneficial attributes of these two kinds of biopolymer to produce small emulsion droplets with good environmental stability. A number of researchers have shown that protein–polysaccharide complexes may have better emulsifying properties than either of the biopolymers used in isolation [23, 110–112]. These complexes may be held together either by physical or covalent interactions, and may be formed either before or after homogenization [3]. A two-step procedure that has been used to prepare protein–polysaccharide complexes at an oil–water interface after homogenization is shown



**Figure 5.15** Schematic representation of production of oil-in-water emulsions containing droplets stabilized by two layers (protein–polysaccharide). A protein-stabilized emulsion is formed first, and then an oppositely charged polysaccharide is mixed with this emulsion.



schematically in Figure 5.15. Ingredients based on protein–polysaccharide interactions will have to be legally acceptable, economically viable and show benefits over existing ingredients before they find widespread utilization in the food industry. It should be noted that gum arabic is a naturally occurring protein–polysaccharide complex that is already widely used in the food industry as an emulsifier [113].

## 5.6 Conclusions

Water soluble polymers can be used to stabilize oil-in-water emulsions provided they have sufficient surface activity, which is usually imparted by the presence of some hydrophobic groups along their backbones. These polymers vary greatly in their ability to form and stabilize emulsions because of differences in their molecular characteristics, such as hydrophobicity, conformation, flexibility, and size. Large random-coil type molecules (such as most polysaccharides and gelatin) tend to stabilize emulsions primarily through steric repulsion, whereas globular molecules (such as globular proteins) tend to stabilize them through electrostatic repulsion. Consequently, emulsions stabilized by globular proteins are highly sensitive to environmental stresses, such as pH and ionic strength, whereas those stabilized by random-coil molecules are more stable. Despite the considerable progress that has been made, a great deal of research is still needed in order to establish the relationship between the molecular characteristics of polymers and their ability to form and stabilize emulsions.

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## Chapter 6

# Polymeric Flocculants

*Gillian M. Moody*

### 6.1 Introduction

The term polymeric flocculants covers a wide range of chemical types from naturally based materials, such as starch, guar gum, etc., to very high molecular weight synthetic polymers based on acrylamide and its ionic counterparts. Included in this chapter is a description of lower molecular weight polymers that are often referred to as coagulants rather than flocculants. However, the distinction between these two terms is rather subtle. The polymeric coagulants are invariably highly cationic in nature and based upon polymers such as polydiallyl dimethyl ammonium chloride (polyDADMAC) and polyamine epi chlorohydrin condensates.

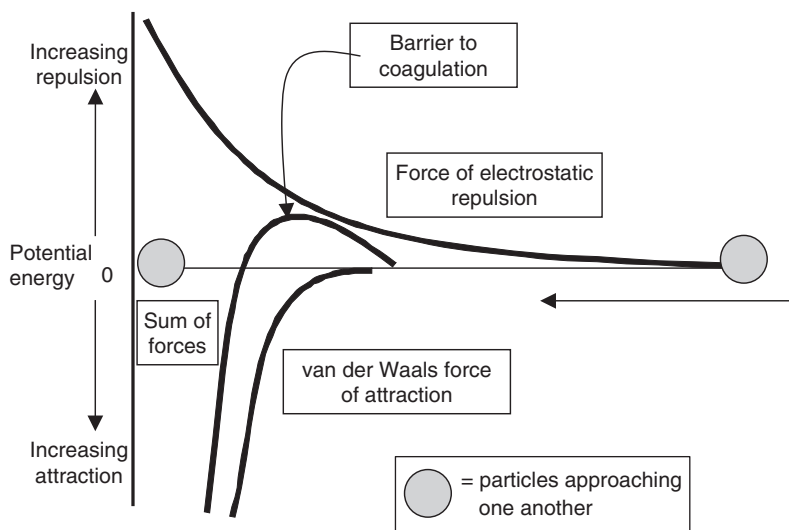
The vast majority of polymeric flocculants are used to aid solid–liquid separation in aqueous systems where the benefits are many and varied. In sedimentation, flocculants and coagulants provide a significant increase in settlement rate and improvement in supernatant clarity. In filtration applications, the rate of filtration is significantly increased and this is usually accompanied by improvement in cake solids and filtrate clarity. In the case of centrifugation, often the whole process is reliant upon the use of high molecular weight synthetic flocculants to give the separation required.

Flocculants are also used as retention and drainage aids in paper production. This is again a solid–liquid separation operation, albeit using very sophisticated and extremely high-speed filtration. Without the use of these reagents it would not be possible to produce paper at the rate that it is today.

This chapter firstly describes the theory of suspensions and flocculation in order to give the reader an insight into how and why coagulants and flocculants are effective. There then follows sections that describe the types of products available and how synthetic products are manufactured and characterised. The latter sections provide brief accounts of the various industrial applications where flocculants and coagulants find use.

### 6.2 Basic theory of suspensions and flocculation

Most particles, in an aqueous suspension exhibit a surface charge. The evidence for this is that when a voltage is applied to an aqueous suspension, colloidal particles migrate to the pole of opposite charge, which in aqueous systems is usually the anode, indicating that the particles exhibit an overall negative charge. There are a number of causes for this surface charge that include; Ionisation of surface groups, uneven distribution of constituent ions, specific adsorption of ions and dipole orientation. This surface charge causes repulsion



**Figure 6.1** Potential energy diagram.

between particles as they approach one another and, any tendency to agglomerate is opposed, thus leading to a stable colloid suspension. The use of polymeric flocculants and coagulants is one means of overcoming this effect.

The DLVO Theory [1] was the first theory to explain the balance of forces that lead to colloid stability or instability. The range of the electrostatic repulsive forces described above is relatively large, of the order of 300 nm. However, in any suspension system, other forces operate, such as van der Waals forces of attraction and these are present at the solid–liquid interface. These forces are relatively strong but they are also short ranged, in the order of 5–10 nm.

A result of these opposing forces is that, as particles approach each other, a maximum in the potential energy curve is observed [2].

However, once the particles are close enough together aggregation will result (Figure 6.1).

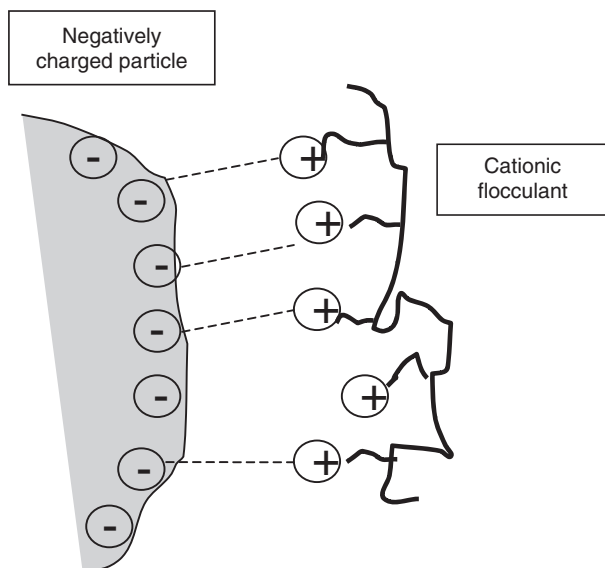
As indicated above, polymeric flocculants and coagulants are used to overcome this barrier. The former, due to their very high molecular weight, are large enough to adsorb onto a number of particles simultaneously [3] and bring them together physically. As this is in effect, bridging the gap between the particles these are often known as bridging flocculants.

### 6.2.1 The mechanism of bridging flocculation

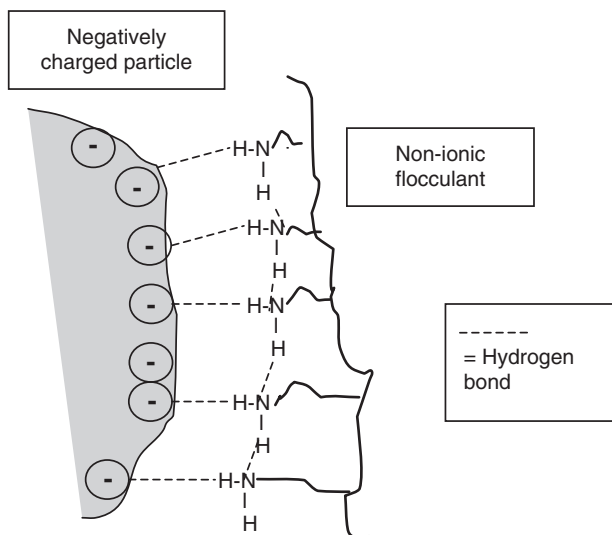
In order to bring about flocculation the flocculant must adsorb onto the solid particles and this occurs in one of three main ways:

- **Electrostatic attraction:** For this to take place the flocculant must contain pendant groups that carry a charge that is opposite to that on the surface of the particle. Therefore, as in the majority of cases the solid surface has a negative charge, this mode of adsorption is most commonly observed for polymers that carry a cationic charge (Figure 6.2).



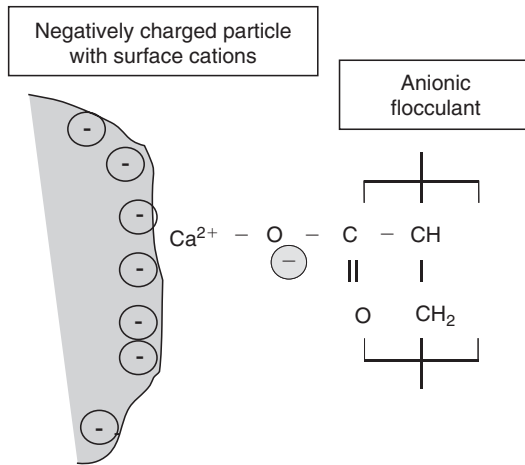


**Figure 6.2** Diagrammatic representation of adsorption by electrostatic attraction.



**Figure 6.3** Diagrammatic representation of adsorption by hydrogen bonding.

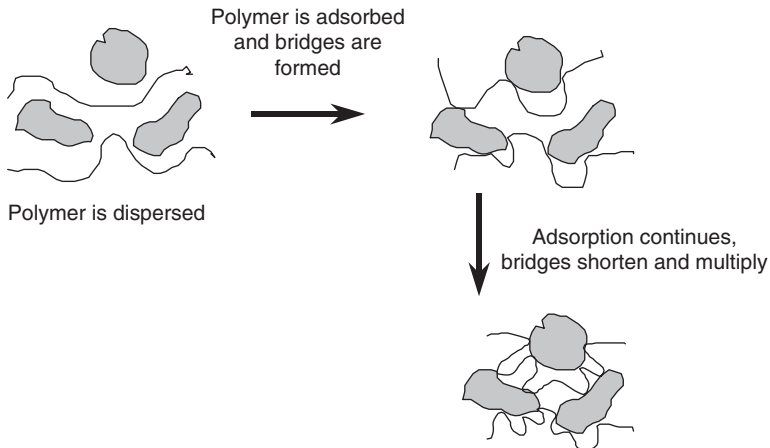
- *Hydrogen bonding*: The  $\delta$  positive charge that is formed on the non-ionic pendant groups of a polymer allow it to adsorb on to the negative sites on the particle surface. Whilst the individual hydrogen bond may be weak the overall adsorption is strong due to the relatively large numbers of bonds that can be formed. Non-ionic products such as polyacrylamide and polyethylene oxide generally adsorb via this mechanism (Figure 6.3).



**Figure 6.4** Diagrammatic representation of adsorption by salt linkage.

- **Salt linkage:** On mineral surfaces, although the overall surface charge is negative it is uneven, mainly as a result of metal ions being available at the particle surface. Salt linkages can be formed between these cationic metal ions and the negatively charged pendant groups on anionic flocculants. This is the mode of adsorption that occurs when flocculating mineral particles, that carry an overall negative charge, with anionic flocculants (Figure 6.4).

Whatever the mode of adsorption, it is anticipated that when a flocculant is added to a suspension it is initially adsorbed onto one or more particles. However, full adsorption does not occur immediately and loops and tails remain extended in solution, and these can then become attached to other particles or to more sites on the same particle. With continued mixing, greater adsorption occurs and the particles are brought together forming a floc as shown in Figure 6.5. The size of the floc formed is dependent on the particle size of



**Figure 6.5** Conventional bridging flocculation.

the material being treated, the dose and type of flocculant added, and the level of adsorption occurring. Floc formation is not a permanent state in that the flocs are sensitive to mechanical shear. Continued mixing after floc formation will cause gradual and permanent floc breakdown although it is unlikely that reversal to the primary particle size would occur. More recently, population balance models [4] have been developed to assist in explaining the complex floc formation and breakdown interactions.

### **6.2.2    *The charge patch mechanism***

Organic coagulants, as a result of their significantly lower molecular weight tend to adsorb onto individual particles. As they are of high positive charge they do have the effect of neutralising the overall negative charge, but more importantly they induce a localised charge reversal. The flocculation occurs through interactions between sites of varying opposite charges on different particles caused by the flat adsorption of polymeric species on to particle surfaces [5]. Patch flocculation is shear sensitive but reflocculation readily occurs under low-shear conditions.

Other means of overcoming the barrier to coagulation include the use of inorganic coagulants such as multivalent metal ion salts that behave in a similar way to polymeric coagulants (although their main mechanism is to reduce the overall charge) adjustment of pH to the isoelectric point so that no overall electrostatic force remains, or by using mechanical agitation that puts energy into the system and can cause coagulation by forcing particles closer together.

## **6.3    Material types**

The global market for water soluble polymers encompasses a wide variety of end-use applications that includes water and waste water treatment, paper manufacture, mineral extraction and processing, enhanced oil recovery and general industrial processing. Advances in the design and synthesis of water soluble polymers has progressively improved their performance and their use has greatly surpassed that of natural polymers such as vegetable starches, casein, gums and alginates, and of inorganic compounds like ferric chloride.

### **6.3.1    *Natural products***

The use of the term natural products, in this instance, refers to products derived directly from a plant or animal source. It includes products that may be chemically modified after harvesting and extraction of the base material and also includes products made by a fermentation route from compounds such as sugar.

Some of the earliest flocculants were based on starch which did find a particular use in the separation of Bayer Process liquors [6], but have since been largely replaced by synthetic flocculants.

At the present time natural products hold only niche applications in the market, that includes the following as examples:

- Starches find use in potable water treatment, and cationic starches are used in paper making, mainly as a strength aid but also for charge reduction mainly by the charge patch mechanism.
- Dextran is a glucan material produced by the action of the extracellular enzyme dextran sucrose on sucrose in solution and it has shown uses for flocculation in alkaline systems, such as those found in the alumina Bayer process.
- Isinglass is used to aid the clarification of beer.
- Carboxy methyl cellulose (CMC) and guar gum that both find use in the paper industry.

Natural products tend to have benefits in terms of biodegradability and approval for use in foodstuffs, but to date they have not, in general, been able to reach the performance levels achieved by synthetic products.

### 6.3.2 *Synthetic polymers*

#### 6.3.2.1 *Polymeric coagulants*

Polymeric coagulants, as stated earlier, are invariably highly cationic in nature, in order that they can neutralise the overall negative charge at the solid–liquid interface. They usually have molecular weights in the order of 250,000 up to 1,000,000. There are a number of different chemical types but the most common are based upon quaternised polyamines, polyDADMAC and polyethyleneimine (PEI).

Organic coagulants are used mainly in low solids environment such as potable water and industrial effluent treatment. They can also be used in combination with high molecular weight flocculants. In particular, the addition of a coagulant improves filtrate and centrate clarities, when the flocculant treatment alone is unable to attain acceptable levels.

#### 6.3.2.2 *Synthetic bridging flocculants*

In order that bridging flocculation can occur the flocculants must be of very high molecular weight. The molecular weight of commercially available products tends to be in the region of 5–20 million. The main product types are those polymerised from acrylamide and its ionic counterparts, such as sodium acrylate and quaternised cationic acrylate esters. The beauty of this range of monomers is that they copolymerise very readily which means that there is an infinite range of possible anionic and cationic contents to allow products to be tailor made to suit particular substrates. Included in this range of monomers are alternative anionic monomers such as sodium acrylamidomethylpropane sulphonate (AMPS) and cationic monomers such as acrylamide propyl trimethyl ammonium chloride (APTAC). In order to provide optimum effect in different solid/liquid separation applications other characteristics that can be varied are molecular weight and structure. This will be discussed in more detail in sections covering synthesis and applications.

The polyacrylamide range of products dominate the flocculant market although, other product types are also used in niche applications and these include polyethylene oxide.

## 6.4 Synthesis of synthetic water soluble polymers

The manufacture of synthetic water soluble polymers on an industrial scale is often conducted on high capacity facilities that have an annual output of 20,000 tonnes or greater. This manufacture has to balance a number of important objectives that include product properties, cost effective performance and customer needs. This has been succinctly summarised as the ability 'to manufacture a product with specified physical and chemical properties at a desired production rate' [7].

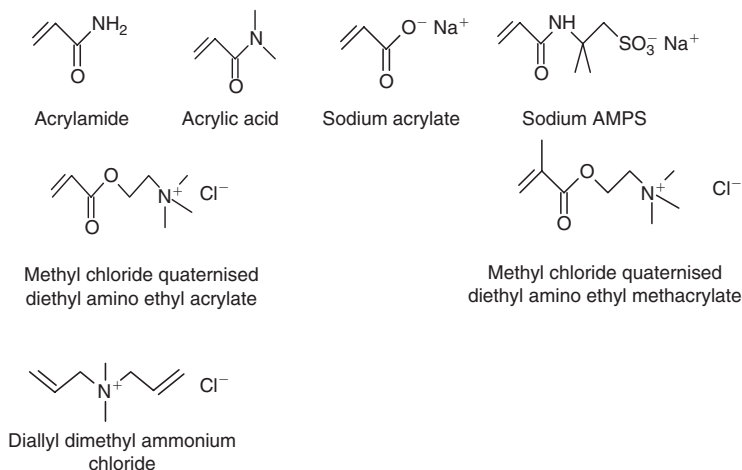
For synthetic water soluble polymers, this capability can be considered as the ability to deliver a product that meets the performance needs of the customer that is provided in the most acceptable physical form having considered issues of transportation, handling, storage stability and polymer make-up and dosing.

There are a small number of key water soluble monomers that have been developed industrially to feed the downstream manufacture of polymers, these are illustrated in Figure 6.6.

These acrylic monomers are reactive and can be polymerised in various forms in both one-phase and two-phase systems (e.g. solution, emulsion etc.).

Typical synthetic water soluble flocculants are polyelectrolytes that are most often based upon copolymers of acrylamide or substituted derivatives. Acrylamide monomer is obtained industrially by the catalytic hydration of acrylonitrile and occurs in both crystalline form and in aqueous solution. The 50% aqueous form is the preferred form for polymerisation systems in which water can be tolerated. Acrylamide has a very fast propagation rate and a high exothermic heat of polymerisation.

Acrylic acid is the most widely used anionic water soluble monomer. Anionic copolymers of acrylamide may be prepared by homopolymerisation of acrylamide followed by hydrolysis to the required extent, by addition of an appropriate amount of alkali, to produce an anionic polymer containing both amide and carboxyl groups. In practice however, monomer mixtures of acrylamide with acrylic acid or one of its alkali metals salts are



**Figure 6.6** Key monomers.

copolymerised together. Other anionic monomers of interest include AMPS in its acid form and as its sodium salt, which remains charged at lower pH than acrylate salts making it less sensitive to divalent metal ions and thereby useful in, for example, seawater applications.

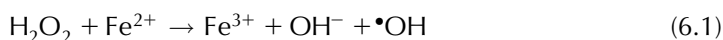
Most water and waste water treatment applications use polymers that are cationic in character that are predominantly prepared by copolymerisation of acrylamide with varying proportions of amino derivatives of acrylic acid or methacrylic acid esters. The most commonly used monomers in this class are dimethyl amino ethyl (meth) acrylate quaternised with methyl chloride or other quaternising agents. Polymerisation is conducted under acidic conditions to prevent base catalysed hydrolysis of the ester linkage. Copolymers with allyl monomers, such as DADMAC are also manufactured however the molecular weight of these polymers is limited by the relative stability of the intermediate radical.

Industrial scale manufacture of these polymers involves a free radical initiation process whereby the free radicals are generated by either thermal decomposition or by a redox process.

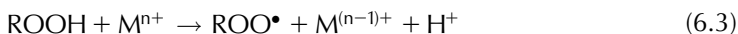
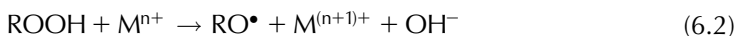
There are a number of commercially available azo initiators that are particularly useful for the polymerisation of water soluble acrylic monomers. Widely used examples include 2,2'-azobis(2-amidinopropane)dihydrochloride, 2,2'-azobis[2-(2-imidazolin-2-yl)propane] dihydrochloride, 2,2'-azobisisobutyronitrile, 2,2'-azobis(2,4-dimethylvaleronitrile) and 2,2'-azobis(2-methylbutyronitrile).

In redox initiation, the free radicals are generated as transient intermediates in the course of a redox reaction that involves an electron transfer process followed by scission to give a free radical. The features of redox initiation, that particularly lend themselves to industrial processes, are the general lack of any induction period before polymerisation begins and a relatively low energy of activation. The low energy of activation allows polymerisation to be carried out from, or at, low temperatures, and this facilitates reaction control of a very exothermic process.

A wide variety of redox initiator pairs are known and can be employed for the purpose. Typical examples include the reaction between hydrogen peroxide and ferrous ion, which results in the formation of hydroxy free radicals:

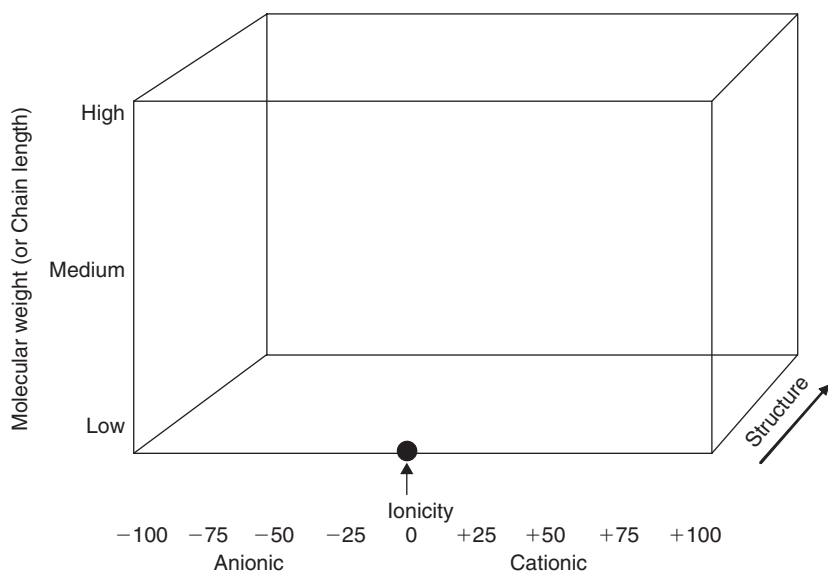


and hydroperoxides in the presence of a metal ion, which may decompose to generate free radicals in one of two ways:



The main aim of the polymerisation process is to produce a polymer having properties that match the needs of the customer. In the earliest phase of development of synthetic water soluble polymers, this effectively meant that once the optimum copolymer composition had been identified, controlling the process to deliver the highest possible molecular weight polymer was key to commercial success.

Increasingly stringent legislation, governing waste water treatment and the disposal of waste products, has driven more recent developments in application techniques and equipment design. These developments have only been possible through the provision of



**Figure 6.7** Polymeric flocculants design space.

polymers that in addition to being very high molecular weight, have been designed to have a specific molecular architecture. This specific architecture could include features such as very narrow or very broad molecular weight distribution, or which could vary from being highly linear in nature through to products that are branched or that contain permanent or transient cross-links between polymer chains.

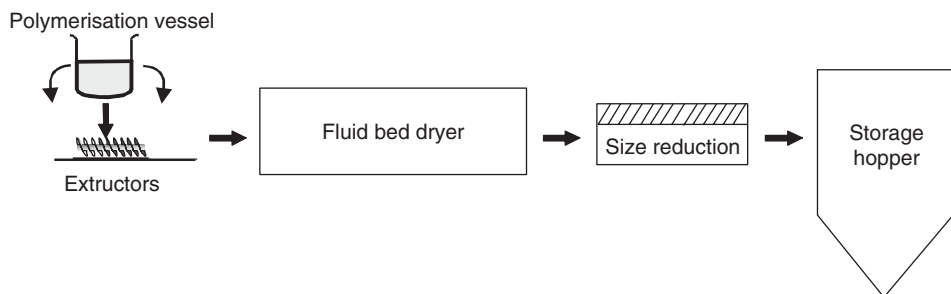
Molecular weight and molecular weight distribution can be manipulated through the addition of a chain transfer reagent. Chain transfer is the reaction of a propagating polymer radical with a transfer agent to yield a 'dead' polymer and a new radical species. Many compounds work well for this purpose, but mercaptans and alcohols are most commonly employed.

Molecular architecture can be influenced by the addition of a monomer that has two or more free-radically polymerisable double bonds. The addition level and reactivity of such a monomer, together with the average chain length of the polymer chains, will determine whether the final product is branched (two dimensional) or cross-linked (three dimensional).

This design of a polymer can be modelled pictorially as the combination of composition, molecular weight and architecture to give a simple design space diagram as illustrated in Figure 6.7.

High molecular weight water soluble polymers are produced commercially in the largest volumes as either finely divided solids or as inverse (water-in-oil) emulsions (which can be optionally dehydrated to provide a higher concentration product). Precipitation polymerisation in electrolyte solution to provide so-called water-in-water polymers is also well known.

The simplest polymers to manufacture are solid grade, or powder products via a batch polymerisation process. This batch process is a one-phase reaction in which all the reactants are added to the vessel prior to the start of the polymerisation process. As the polymerisation progresses the aqueous monomer mix forms into a solid mass. The onset of this gelation occurs at quite low monomer conversion, and manipulation of the polymerisation is not



**Figure 6.8** Batch polymerisation of powder grade polymer.

possible once the redox initiators have been added. The solid mass of polymer is subsequently extracted from the vessel before a process of drying and size reduction to give a powder product that typically has an average size of several hundred microns in diameter. A schematic of this process can be seen in Figure 6.8.

Solid grade polymers are also manufactured on an industrial scale using a two-phase, water-in-oil process. This involves dispersing aqueous monomer into a volatile hydrocarbon solvent to form spherical droplets that have a typical diameter of several hundred microns. Redox or thermal initiators can be used to effect polymerisation. The final product is a non-dusting, free flowing bead that can be graded by size to meet customer requirements.

A significant proportion of water soluble polyelectrolytes are produced as liquid grade products that are predominantly inverse, that is water-in-oil emulsions. In this process the aqueous monomer is dispersed in a non-aqueous continuous phase through a combination of high-shear mechanical mixing and the use of low hydrophile-lipophile balance (HLB) surfactants such as sorbitan mono oleate or similar. The resultant dispersion contains droplets having an average particle diameter of only about 1  $\mu\text{m}$ .

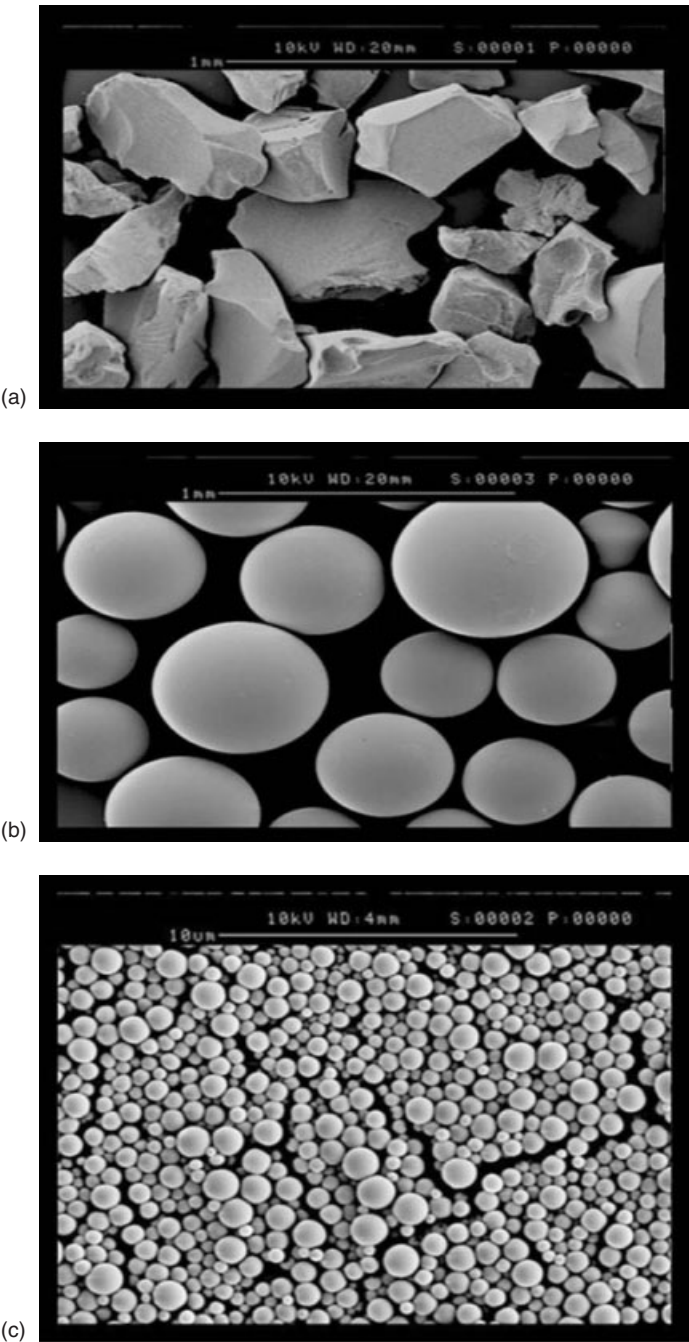
Polymerisation is carried out via a semi-batch (semi-continuous) process that allows reactants to be added during the polymerisation. It is usual for at least one of the redox initiators to be added as a metered feed over the course of the reaction. Other reactants can be added in order to control desired properties such as molecular weight distribution. Temperature control over the course of the polymerisation is also possible, particularly as the oil phase helps to dissipate the heat of polymerisation. Overall the semi-batch polymerisation technique is more versatile than the batch process and, as a consequence, it is possible to better manipulate polymer properties via this route.

Inverse-emulsion polymers have an active polymer content generally ranging from about 25% to 50% dependent on the monomer(s) employed. Non-ionic surfactants are added to the final product to facilitate rapid dissolution of the polymer when it is added to water in the end-use application.

The relative size and shape of the polymer particles produced from these different process can be see in scanning electron micrographs in Figure 6.9.

Both one-phase and two-phase polymerisation systems lend themselves to continuous polymerisation processes in which all the reactants are fed to the process continually and polymer is removed continually. Continuous processes are particularly useful for the manufacture of high volume products and, although initial capitalisation can be more expensive, operating costs are reduced in comparison to batch or semi-batch processes.





**Figure 6.9** Scanning electron micrographs of (a) Powder, (b) Bead and (c) Inverse emulsion polymers.

The final consideration in manufacturing water soluble polymers on an industrial scale is to ensure that the environmental impact of the product is controlled to satisfy all regulatory requirements. This is of particular importance for example in the treatment of waste water, and even more so in the treatment of drinking water where there are very severe constraints on the level of residual monomer that is permissible in the final product. Treatment of the product is usually carried out when the polymerisation is complete and techniques vary from simple heating of the polymer or the addition of further initiator through to UV irradiation of the final product.

## 6.5 Characterisation of industrial water soluble polymers

Chemical type, ionic character, viscosity, average molar mass and molar mass distribution are properties of a polymer that may be characterised. Determination of chemical type may be accomplished using a variety of techniques such as infrared spectroscopy, GC-pyrolysis, NMR and elemental analysis techniques.

### 6.5.1 *Ionic character*

The most useful water soluble polymers carry a net charge, hence the term polyelectrolyte. As described earlier, the net charge may be anionic, for example by introducing carboxylic acid groups, or cationic as is the case with quaternised acrylic esters or DADMAC. The extent of ionicity in a copolymer influences the behaviour of the polymer in solution and is therefore a useful characteristic to quantify.

A simple qualitative test for many aqueous polymers is simply to add a dilute solution of the polymer under investigation to two further solutions, one of which is known to be anionic and the other cationic. If a hazy precipitate forms in the cationic solution it is known that the test solution contains anionic polymer and vice versa.

For polymers containing carboxylic acid, for example copolymers of acrylic acid, a simple pH titration may be used to determine the quantity of anionic groups present. Anionic polymers containing sulphur may be analysed by elemental techniques such as inductively coupled plasma [8] after microwave digestion in strong acid solution.

Cationic groups within a polymer can be quantified by colloid titration. A dye, such as orthotoluidine blue, is added to a dilute solution of the cationic polymer. Upon titration with potassium polyvinyl sulphate the cationic polymer forms a complex until the entire polymer is used up. At this point the additional potassium polyvinyl sulphate forms a complex with the dye and there is a colour change from blue to pink.

For structured polymer solutions where polymer chains are tangled, not all the ionic groups are accessible by the reagent. These solutions may require to be subjected to a high degree of shear, from a stirrer or blender, prior to conducting the titration.

During the colloid titration, use may be made of this entanglement and titration values before and after the application of high-shear provides an indication of the degree of structure or cross-linking. The larger the difference in the value obtained the higher the degree of structure can be assumed.

### 6.5.2 Viscosity

The viscosity of a fluid is a measure of the frictional resistance it offers to an applied shear force [9] and is an important characteristic of polymers when applied to dilute solutions.

Assuming laminar flow, the profile of a liquid flowing through a narrow capillary is parabolic and viscosity,  $\eta$ , is proportional to the pressure gradient,  $\Delta P$ , according to Poiseuille's equation:

$$\eta = \frac{\pi r^4 \Delta P}{8 L Q} \quad (6.4)$$

where  $r$  is the radius of the capillary,  $L$  is the length of the capillary and  $Q$  is the flow rate through the capillary.

Measurement of viscosity is concentration dependent and in practice, the viscosity or rather the specific viscosity,  $\eta_{sp}$ , equation 5, is measured at several concentrations,

$$\eta_{sp} = \frac{\eta - \eta_0}{\eta_0} \quad (6.5)$$

where  $\eta$  is the viscosity of the solution and  $\eta_0$  the viscosity of the solvent.

Plotting  $\eta_{sp}/c$  versus  $c$ , where  $c$  is the concentration, and extrapolating to infinite dilution yields the intrinsic viscosity (IV).

Viscosity measurements are made either in a glass capillary such as a suspended-level viscometer or in a stainless steel differential viscometer. The measurement of the IV of a polyelectrolyte is hampered by intra- and inter-molecular ionic repulsion, and it is necessary to add buffers and electrolyte to the solution to suppress these forces.

IV is used to calculate average molar mass using the Mark-Houwink-Sakurada relationship, equation 6,

$$\eta = k M_v^a \quad (6.6)$$

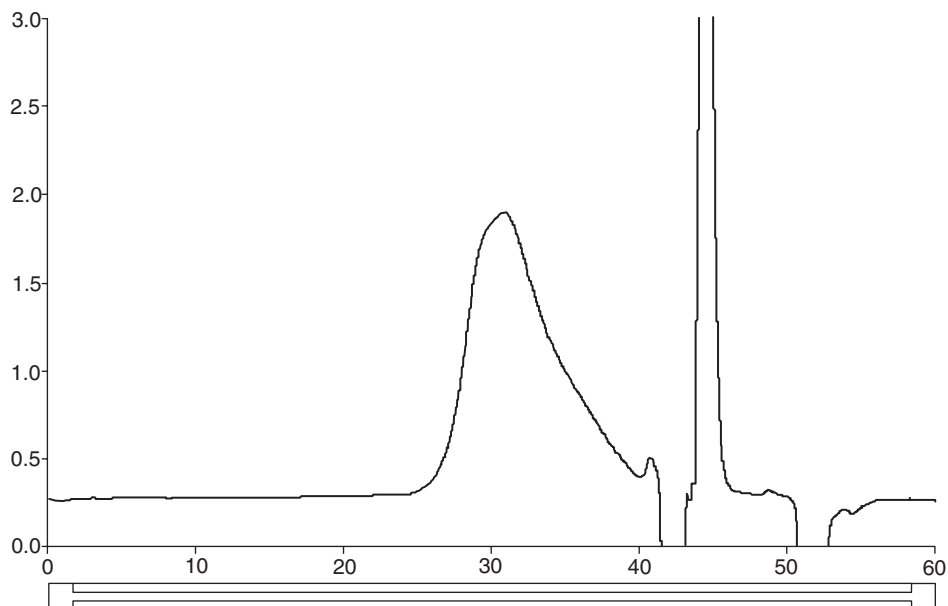
where  $k$  and  $a$  are constants, the latter relating to molecular structure. Both constants are dependent on solvent, polymer type and temperature.  $M_v$  is the viscosity average molar mass and like IV is an average measurement of the bulk sample. For more detailed characterisation and an understanding of the range of molecular sizes or molar masses, a separation technique such as size exclusion chromatography (SEC) must be employed (also known as gel permeation chromatography (GPC)).

### 6.5.3 Molar mass

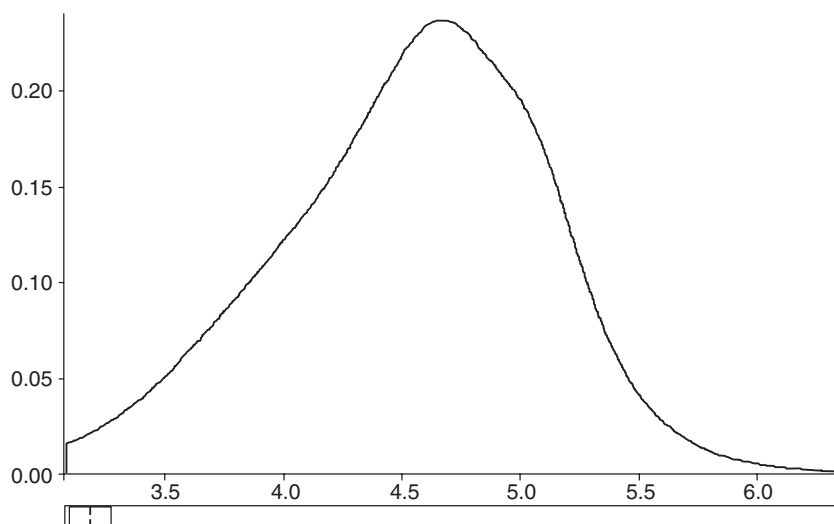
During SEC, polymer molecules in solution are separated according to hydrodynamic volume on a column packed with an inert porous material such as a highly cross-linked polymer or silica. Separation occurs because large molecules are unable to penetrate all of the pores in the packing. Successively smaller molecules spend more time in the packing material and elute later.

By calibrating the column or column set with a set of standards, a calibration curve of retention versus the logarithm of molar mass is constructed so that molar mass averages may be calculated for unknown polymers. Figure 6.10 is an example chromatogram of a separation of a polyDADMAC coagulant polyelectrolyte. The molar mass distribution, see Figure 6.11, is relative to the calibration standards used, polyethylene oxide in this example.

This process, often called conventional calibration, has several limitations. Separation is based on size, not molar mass, so results are relative to the calibration standards. The chemical types of standards are limited and may not be available for copolymers. The range of molar masses is also limited and calculation of higher molar mass samples may rely upon extrapolated parts of the calibration curve. High molar mass polymers such as flocculants may block column frits and pores of the packing, and the relatively high pressure may degrade the polymer by shearing.



**Figure 6.10** Differential refractive index detector chromatogram of a coagulant.



**Figure 6.11** Molar mass distribution of a coagulant.

Polyelectrolytes often interact with the column packing in aqueous systems, and it is necessary to use simple electrolytes and buffers to prevent or at least subdue unfavourable interactions that would otherwise lead to non-size exclusion behaviour. If the polymer contains hydrophobic groups, perhaps in a copolymer, addition of a less polar solvent such as methanol or acetonitrile may be necessary for successful elution.

The limitations of conventional calibration techniques are addressed by multiple detector techniques. On-line viscometers [10] and light scattering detectors [11, 12] enable more information to be elucidated from a chromatographic run.

During a light scattering experiment the excess Rayleigh scattering,  $R_\theta$ , which is the ratio of scattered to incident radiation minus scattering from the solvent alone, is measured and is related to the weight average molar mass,  $M_w$ , by the following relationship,

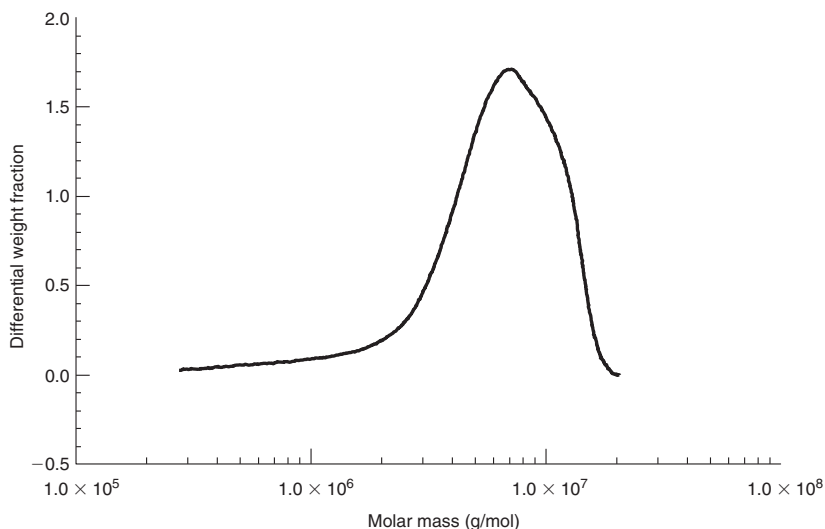
$$\frac{Kc}{R_\theta} = \left[ \frac{1}{M_w P_\theta} \right] + 2A_2c \quad (6.7)$$

where  $c$  is the solution concentration,  $K$  is a constant (containing several terms),  $A_2$  is the second virial coefficient that gives an indication of the solute and solvent interaction and  $P_\theta$  is the angular dependence of the excess Rayleigh scattering.

During SEC where the concentration is generally low, the second term is assumed to be small and in most cases is eliminated.

For small molecules there is no angular dependence of the scattering function,  $P_\theta$  is 1 and  $M_w$  may be determined at any angle, but for larger molecules there is an angular dependency and  $M_w$  must be determined at zero angle. In practice this is achieved by measuring at a low angle (assumed to be near zero) or by measuring at several different angles and extrapolating back to zero angle.

Figure 6.12 is an example of a molar mass distribution of a cationic copolymer flocculant of acrylamide measured using a SEC system coupled to a differential refractive index detector and a multi-angle light scattering detector.



**Figure 6.12** Molar mass distribution of a cationic acrylamide copolymer.

On-line viscometers allow measurement of an intrinsic viscosity distribution (IVD) and in combination with light scattering the two techniques provide a powerful array of tools to investigate structural characteristics and molar mass averages.

Other separation techniques may be employed when polymer molecules become too large to put through a SEC column. One of the most promising techniques that have been developed over recent years is field-flow fractionation (FFF) [13]. Originally developed by Giddings, separation occurs in a channel rather than a column and there is no shear stress on the sample.

## 6.6 Solid/liquid separation

Solids separation from liquid is a common requirement in many industries. Typically used for the treatment of industrial and municipal wastes, and in mineral processing operations where water is used as the vehicle to grind and separate minerals via differential dissolution, precipitation, flotation or density.

The solid–liquid separation equipment used depends on suspended-solids particle size, and increases in complexity or time duration as particle size reduces. The intervention of adsorbing polymers, such as coagulants and flocculants can encourage particles to gather together as combined agglomerates and behave as larger particles.

The benefit of increasing particle size, with respect to sedimentation, can be illustrated by the use of Stokes Law that states:

$$\text{Settling Velocity} = \frac{(\rho - \rho_0)d^2G}{18\mu} \quad (6.8)$$

where  $\rho$  = density of solid,  $\rho_0$  = density of liquid,  $d$  = diameter of particle,  $G$  = centrifugal force and  $\mu$  = viscosity of liquid.

The above equation makes a number of assumptions; the particle is spherical, the concentration of suspended solids is low and the suspension is in a quiescent state. However, although this somewhat simplistic approach does deviate from the practical situation, it does identify that the relationship between particle size and settling velocity is exponential. Therefore, as particle size increases this has a significant impact on settling velocity.

This is the effect that is observed when coagulation and flocculation is induced and provides a significant beneficial effect in terms of solid–liquid separation efficiency. Although the Stokes Law equation above deals with sedimentation, a similar improvement in efficiency is observed when dealing with filtration and centrifugation.

The following examples describe the typical hardware utilised to carry out solid–liquid separation on an industrial scale.

### 6.6.1 Clarifiers

Clarifiers are used for the removal of low concentrations of suspended solids, where their presence would interfere with downstream recovery processes, for example copper sulphate

solution feed to electrowinning whereby electrode quality can be impaired. They are also used where the quality of the water is of utmost importance, for example for discharge to a water course.

Low aspect ratio cylindrical tanks are employed to give a long residence time and quiescent conditions for sedimentation. This can often be followed by filtration to 'polish' out the uncaptured material. A typical example is the Solids Contact Clarifier [14].

In clarifiers, polymeric coagulants are used to aid in the capture of fine particles.

### 6.6.2 Thickeners

Thickeners are employed where the solids content is somewhat higher than that encountered in a clarifier. The purpose here is to remove as much liquid as possible via the upper surface exit of a gravity separation vessel, whereby the solid material reports to the base due to its higher density, and is routinely removed. Flocculants and coagulants are employed to improve throughput several fold by enhancing the initial sedimentation step and controlling dewatering in the compression zone [15]. This continuous operation results in a several fold increase in solids concentration from feed to underflow. Clarity of supernatant is often a secondary criterion. The limit to the operating throughput, in tonnes per hours, is related to the sedimentation speed of the flocculated solids via the relationship established by Coe and Clenger [16].

A wide variety of thickener designs [17, 18] are available to suit specific criteria such as high rate, or to maximise underflow solids (e.g. paste thickeners), a typical example is illustrated in Figure 6.13.

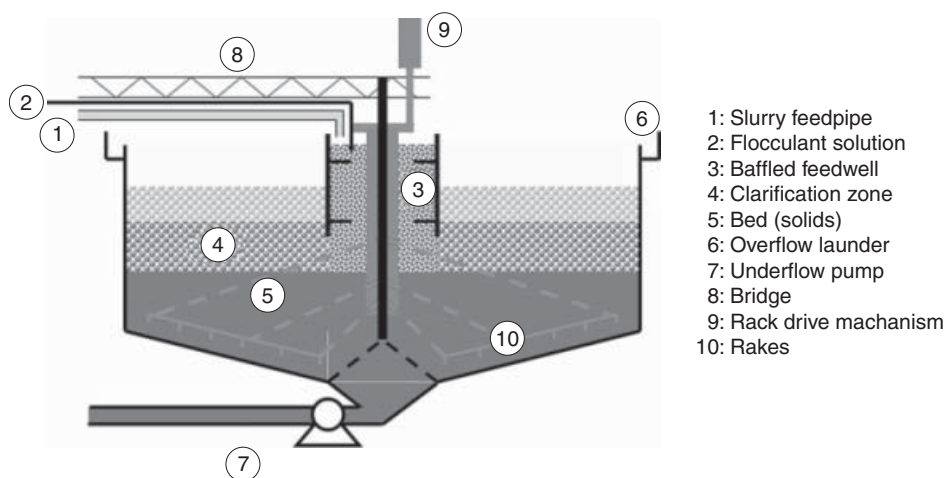
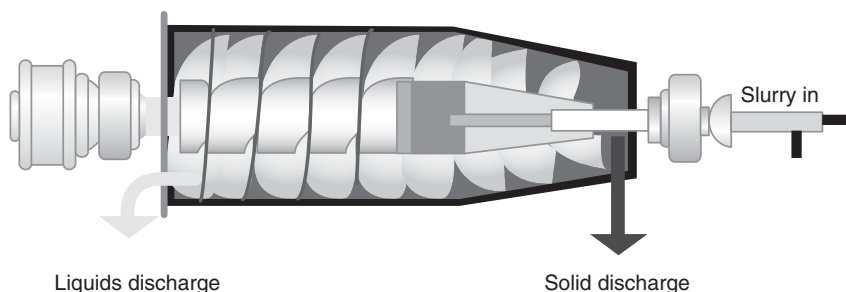


Figure 6.13 Schematic of a typical thickener.

### 6.6.3 Centrifuges

A centrifuge can offer an alternative accelerated process via the increased force of gravity. A solid bowl centrifuge operates as the sedimentation vessel and there are numerous



**Figure 6.14** Typical centrifuge installation. Published by kind permission of Pennwalt Ltd.

designs [19, 20]. A relatively high dosage of flocculant is required to resist the destructive high-shear conditions [21]. A typical example of a solid bowl centrifuge is illustrated in Figure 6.14 (schematic).

### 6.6.4 Filters

Various designs are used to achieve either a clarification of liquors, or a significant increase in solids concentration resulting in the production of a wet solid filter cake of minimal moisture content. This can be driven by either an applied pressure to the substrate over a porous filter medium (i.e. pressure filtration), or a vacuum applied behind the filter medium (vacuum filtration). The process can be on a batch basis, or via a continuous operation where, by a mechanical rotary means, new filtration areas are offered to the substrate. Chemical conditioning, including flocculation and coagulation, can be used to increase throughput, cake solids or fines capture.

#### 6.6.4.1 Deep bed filters

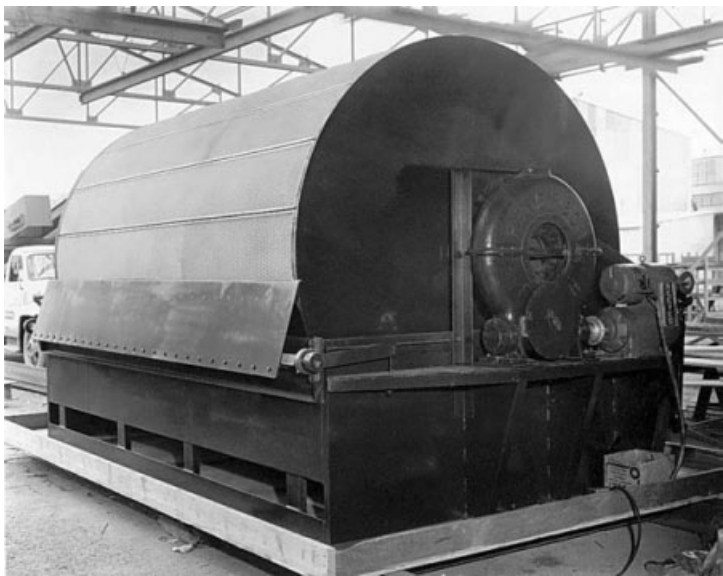
This filtration technique is used to remove low levels of finely dispersed suspended solids, often as a polishing step for the clarified liquid following other primary treatments. A bed of particulate solids acts as the filter medium, and the head of substrate is used to hydraulically drive the slow flow of liquid through the bed. This gives maximum opportunity for particles larger than the pore spaces to be trapped and removed later by backwashing. Beds of multimedia of different densities can be used to create layers of differing particle size, thus achieving a progressive size extraction [22].

#### 6.6.4.2 Vacuum filters

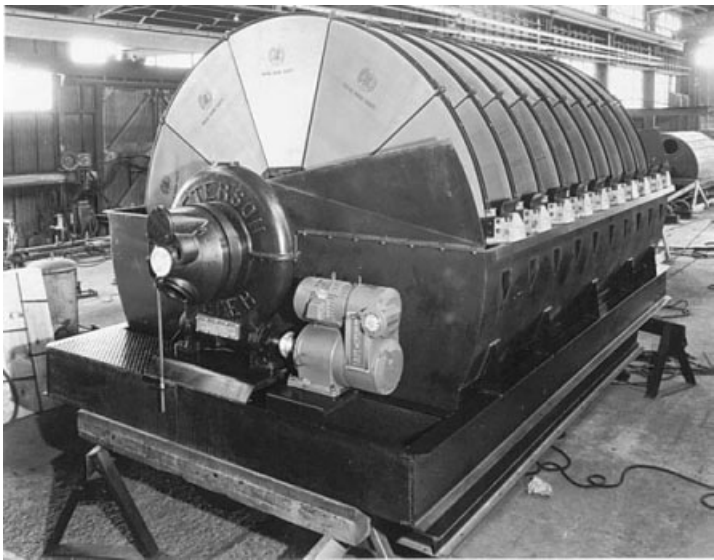
There are a variety of designs [23] of vacuum filter, the selection of which depend strongly on the particle size distribution and density of the suspended solids in the feed slurry. The main types are drum, disc or horizontal belt filters. In each case the filter medium is usually a porous cloth, the permeability of which is chosen to suit the feed particle size.



Coagulants and flocculants can enable a more open, faster medium to be employed, and still retain fines capture, thus providing an increase in throughput whilst achieving acceptable cake moisture contents [24, 25]. Examples of rotary drum filters and rotary disc filters are shown in Figures 6.15 and 6.16 respectively.



**Figure 6.15** Rotary drum filter. Published by kind permission of Peterson Filters Corporation.



**Figure 6.16** Rotary disc filter. Published by kind permission of Peterson Filters Corporation.

### 6.6.4.3 *Pressure filters*

These are normally chosen for finer particle substrates which require a greater differential pressure (greater than the 14.7 psi maximum differential achieved under full vacuum) in order to achieve a practical rate of filtration, or to minimise cake moisture content and again there are many different designs of filter [26, 27]. Several employ a batch process such as the common Plate and Frame Filterpress, but can be semi-continuous as in the Automatic Pressure Filter whereby a continuous filter cloth enables feed, discharge and belt washing to be operated in sequence or fully continuous pressure belt filters.

### 6.6.5 *Flocculant selection*

Natural polymers such as modified starch, guar gum or dextran are employed to boost the particle size of substrates but, due to their lower molecular weight relative to synthetics, their use is mainly focused on improvements to fines capture and clarity.

Synthetic polymers can achieve large aggregate structures which can deliver the highest throughput requirements in terms of settlement or filtration rates, especially in high rate equipment where high-shear conditions apply at the floc formation stage.

### 6.6.6 *Coagulant use*

The water in many circuits often has sufficient natural levels of cations, especially multivalent ions of calcium and magnesium, to destabilise the repulsive surface charge on the finer sized particles to allow natural aggregation, suitable for secondary bridging flocculation. Where this is not the case, the application of inorganic or organic coagulants is employed.

### 6.6.7 *Operating strategies*

Bridging flocculation is achieved by collisions between disparate particles and individual molecules of high molecular weight water soluble polymers extended in solution [28]. Adsorption is weak, and the delicate clusters are simultaneously being torn apart by the very mixing energy that is required to provide the frequency of collisions. On balance, due to favourable surface energy interactions, a multi-particle floc structure results, which achieves an enhanced solid-liquid separation and release of clean water. Therefore an extended period of low intensity mixing favours maximum efficiency of flocculant use. Unfortunately, due to the high slurry throughput volumes, this residence time is not available, so other strategies are used to maximise the effect.

#### 6.6.7.1 *Influence of flocculant solution concentration*

Flocculants are designed to be very attractive to solid surfaces and adsorption takes place almost instantaneously. However this can lead to inefficient distribution, as polymer can be adsorbed by only the first part of the feed that it contacts, leaving other solids untreated.

This effect is exacerbated by the difficulty of dispersing the viscous polymer solution into a viscous slurry. Flocculant solution is therefore applied at as dilute a concentration as possible, typically  $<0.3\%$ . However, this would require an excessively large flocculant dissolution facility. The compromise is often to maximise the preparation of a high concentration stock solution, for example  $0.5\text{--}1.0\%$ , and provide the facility for in-line dilution close to the polymer solution injection. The benefits of this are often overlooked.

#### *6.6.7.2 Effect of dilution of feed solids*

The efficiency of generating polymer/solids collisions with minimum floc breakdown is reduced in a viscous and crowded particulate suspension. Cost and efficiency improvements can be gained via feed dilution with water or recycled clarified liquor.

#### *6.6.7.3 Point of addition*

The placement of the injection point of the flocculant solution can have a critical influence on the resulting performance. Generally a point of turbulence is chosen to ensure homogeneous distribution of polymer into the substrate. The point of addition also defines the mixing time. This needs to be sufficient for solids capture but, at the same time, not to give excessive floc rupture.

#### *6.6.7.4 Multi point addition*

The conflict between capture and size can be overcome by applying the flocculant at two or more points. The first dosage is exposed to sufficient mixing to maximise solids capture. A late addition under lower-shear conditions finally maximises bridging flocculation.

#### *6.6.7.5 Solids recirculation*

The recycling of treated solids into the flocculation initiation zone can enhance clarification. This increases the opportunity for collisions and introduces polymer-coated solids to aid in further solids capture.

## **6.7 Mineral processing**

Clay is a common mineral contaminant and water recovery from discarded effluent is problematic as a result of its particle size being  $<10\text{ }\mu\text{m}$  due to hydrolytically weakened delamination. At a presence of hundreds to thousands of tonnes per day at each site, solid-liquid separation becomes a significant cost to the viability of operation.

The value streams in mineral processing also generate similar separation demands through the operations to separate and concentrate the products in the form of particulates or solutions.

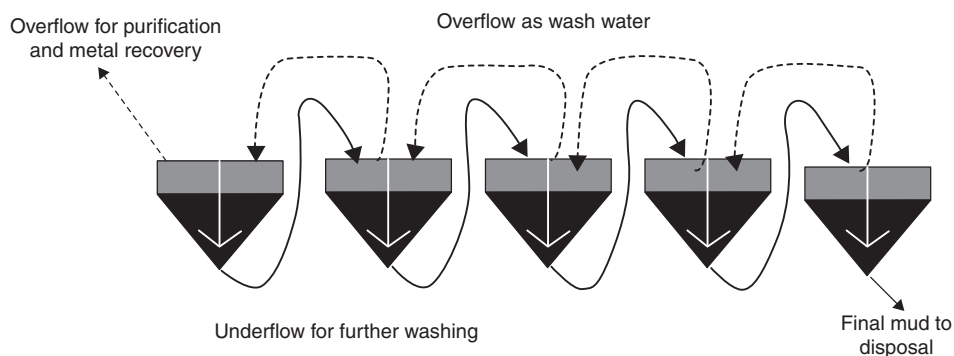
Typically the flocculants used are anionic or non-ionic in nature and, as a result, attachment to particles is via salt linkages or hydrogen bonding.

Choice of optimum polymer tends to be carried out by empirical testing [29] due to the complex nature of the interactions between polymer, suspended solids and dissolved solids in a substrate. However, the following provides some general guidelines:

- Acidic substrates, examples include copper, nickel and zinc leach slurries, are often best treated using non-ionic or low anionic ( $<15$  mol%) copolymers, as the higher anionic ratio polymers tend to precipitate in acidic conditions.
- Mid-range anionic copolymers (15–45 mol%) are often used to treat neutral slurries such as coal tailings or sand and gravel effluents.
- For highly alkaline slurries, typically those found in the alumina industry [30] copolymers of higher anionic content ( $>45$  mol%) predominate.
- The smaller the particle size of the suspended solids, the higher the flocculant demand and the more difficult they are to dewater [31].
- Low to medium molecular weight products are often best for vacuum filtration, pressure filtration and sedimentation where a relatively slow settlement rate ( $<3$  cm/min) is required.
- High molecular weight products offer benefits for sedimentation where higher rate thickeners are employed.
- Treating mineral substrates using a pressure belt filter often requires the use of a two-component treatment, typically a high molecular weight anionic copolymer followed by a cationic coagulant. This provides a smaller, tighter floc that doesn't stick to the belts.
- The higher the colloidal clay content the higher the flocculant demand and the more likely the need for a coagulant (organic or inorganic) pre-treatment.

Below are examples of typical mineral processing operations that illustrate the position of solid–liquid separation within the overall process.

- Aluminium production whereby sodium hydroxide leaches sodium aluminate in bauxite, from insoluble gibbsite. A sedimentation procedure, usually in the form of a counter-current thickener wash train (see Figure 6.17) is followed by polishing filtration prior to precipitation of alumina trihydrate which is filtered prior to smelting. The flocculants used are typically 100% anionic homopolymers at the front end of the wash



**Figure 6.17** Illustration of a counter-current decantation washtrain.

train, and gradually decreasing in anionic copolymer ratio as the alkalinity decreases down the wash train.

- Nickel production by high pressure sulphuric acid leaching requires a grinding stage followed by sedimentation to concentrate the suspension feed to autoclaves. Dissolved iron is then selectively precipitated followed by sedimentation to recover the pregnant liquor-containing nickel and cobalt. The flocculants at this stage tend to be high molecular weight non-ionic or low anionic copolymer ratio in nature. This stream is treated with ground magnesium oxide to precipitate the nickel/cobalt hydroxides, which then undergoes sedimentation, with the concentrated underflow subsequently vacuum filtered. The filter cake is re-dissolved in ammonia and carbon dioxide, and pressure filtered to remove minor undissolved solids. The clean liquor is processed to precipitate remaining contaminant levels of manganese, iron and magnesium. A final filtration stage produces the liquid feed to solvent extraction.

## 6.8 Oil industry applications

### 6.8.1 Water injection systems

As oil reservoirs age and become depleted, a common technique employed is to inject water into the formation to maintain pressure in the reservoir in order to displace oil. The water must be treated by a combination of equipment and chemicals, to remove particulates to avoid reservoir damage, minimise corrosion, scale and bacterial activity.

Particulates, for example inorganic materials (sand, silt), marine plankton and detritus from marine plankton, are removed by filters.

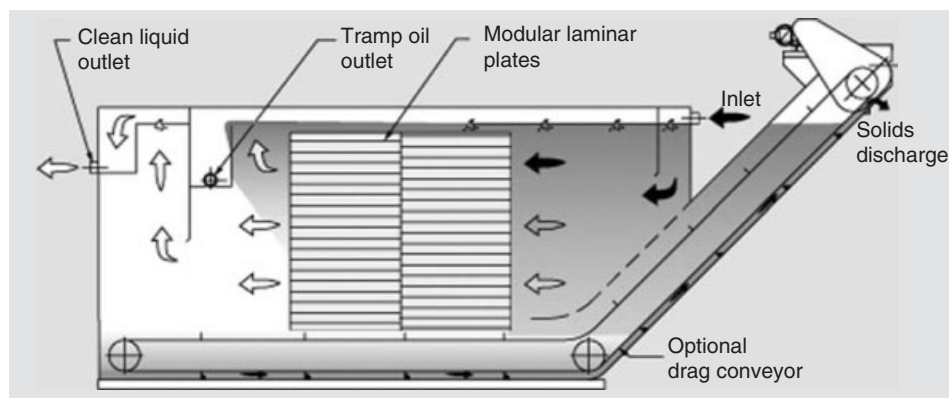
There are two stages of filtration. The first being a coarse filter that protects the plant from ingress and remove the load from the fine filters. Polypropylene cartridge filters are examples of the type of filters used at this stage. The second stage is the fine filtration step, the aim here is to typically remove greater than 98% of the particles that are 2  $\mu\text{m}$  or larger in size. Sand or anthracite deep bed filters are often used in this application.

Polymeric coagulants are applied to improve the efficiency of the fine filters.

### 6.8.2 Oily water clarification

In oil-containing aqueous effluents the oil is present as finely dispersed droplets in a relatively clean water phase, for example oilfield produced water, refinery process water, ballast water from cargo tankers [32]. Factors preventing coalescence include the droplet's negative electrostatic charge, stabilisation by surface active components and steric stability caused by fine solids.

These can be clarified relatively easily in separation equipment such as corrugated plate separators, flotation units, hydrocyclones or centrifuges. An example, the Compact Clarifier, is shown in Figure 6.18. The efficiency of the equipment is usually enhanced by the application of flocculants/coagulants which draw the finely dispersed oil droplets and suspended solids together into larger particles which are separated more effectively, in a manner that is akin to suspended-solids flocculation. The oil droplets have a substantially



**Figure 6.18** The monroe compact clarifier. Published by kind permission of Monroe Environmental Corporation.

negative surface charge and are generally receptive to cationic polymer treatments. Typically polyamine type coagulants are applied at around 2 mg/l to enhance oil coagulation. These may be used alone or in combination with inorganic coagulants such as ferric chloride or ferric sulphate. In addition the use of another class of chemicals, di alkyl dithiocarbamate salts, may also be used to enhance oil coagulation.

Further benefits can be obtained by the use of high molecular weight cationic acrylamide copolymers that build up aggregate size and offer shear resistance to breakdown.

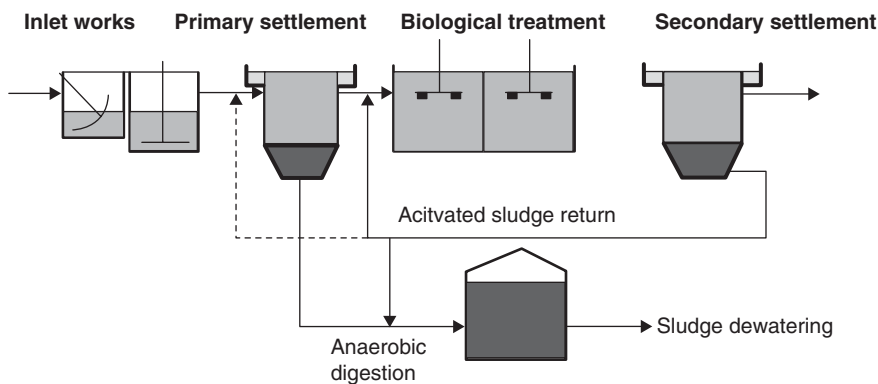
These custom oil/water separators are designed per American Petroleum Institute standards (API) for above and below ground installations. Prefabricated assemblies are available up to 14-ft wide by 140 ft long [33, 34].

## 6.9 Municipal wastewaters and sludges

Raw, untreated sewage contains a complex mixture of mainly organic substances present in dissolved form or as colloidal and suspended-solid particles. Treatment to reduce the polluting load of raw sewage is carried out at a municipal wastewater treatment plan [35, 36], and involves a number of process stages, as illustrated in Figure 6.19.

Essentially, the main process involves the following: (1) preliminary treatment to remove gross solids and grit; (2) primary settlement to remove coarse suspended solids; (3) biological treatment (usually by means of the activated sludge process) to convert soluble and colloidal organics to suspended solids; and (4) secondary settlement to remove the suspended activated sludge biomass. The bulk of the polluting organics having been removed from the sewage, it is then acceptable for discharge to a watercourse.

Polyelectrolytes may be used to assist solid-liquid separation at the primary and secondary stages. A high molecular weight, medium copolymer ratio cationic polyacrylamide can be used on its own as a flocculant to improve removal of suspended solids and thus increase the efficiency of the settlement basins. More advanced chemical treatment can be carried out at the primary stage to assist removal of colloidal and some dissolved organics



**Figure 6.19** Schematic of typical municipal wastewater treatment.

and phosphate thus reducing the loading on the biological stage. This involves use of a low molecular weight, highly cationic polymer (polymer coagulant) in conjunction with an inorganic coagulant such as a ferric or aluminium salt. The use of the polymer coagulant, which is typically a polyamine or polyDADMAC in this application, helps minimise the inorganic coagulant dose thus reducing sludge production and maintaining the required level of alkalinity needed for subsequent nitrification. Settlement of the fine floc produced by coagulation can be assisted using a third component to build up the floc size and improve particle capture, namely, a high molecular weight, anionic or cationic polyacrylamide.

Whilst polymers are useful for assisting the various solid–liquid separations pertaining to the main treatment process, their biggest use by far is in the thickening and dewatering of sludges arising from the main treatment stages. As indicated in Figure 6.19, concentrated settled solids (containing from 1% to 10% dry matter) are drawn off at the primary and secondary stages. Some form of thickening, particularly of secondary sludge, may be employed which often involves the use of a cationic polymer. Mixtures of primary and secondary sludges are usually processed by mesophilic anaerobic digestion, which converts the sludge from a malodorous, putrescent and heterogeneous slurry to a relatively innocuous, homogeneous liquid waste suitable ultimately for disposal. Further handling and disposal of the sludge, whether it is by landfill, utilisation in agriculture, or incineration, usually requires that it first be dewatered to convert it from a liquid containing typically 2–5% dry matter to a wet cake containing 25–30% dry matter.

Most modern sewage works carry out thickening and dewatering by mechanical means using one or more of the following:

- Drum thickener
- Moving-belt thickener
- Dissolved-air flotation (DAF) thickener
- Centrifuge (standard for high solids)
- Filter belt press
- Filter press (chamber press)
- Screw press
- Rotary vacuum filter (USA)

Whatever method is employed it is necessary to first condition the sludge before dewatering, which, in most cases, is exclusively carried out by addition of a cationic polymer (usually a polyacrylamide) or sometimes a combination of two polymers applied in sequence, or an inorganic pre-conditioner followed by polymer. Some filter press operations still use inorganic conditioning systems, such as ferric chloride and lime, without polymer; however, these are now few and far between.

Many factors influence the flocculation and dewatering process, including:

- Composition of raw sewage.
- Operation and type of sewage treatment processes.
- Ratio of secondary to primary sludge.
- Type and efficiency of sludge stabilisation process (e.g. anaerobic digestion).
- Sludge age.
- Sludge solids.
- Type of dewatering machine.
- Operational settings of dewatering machine.
- Required results (filtrate/centrate quality and cake dry solid content).
- Quantity of dilution water available for polymer.
- Polymer make-up equipment available.
- Level of mixing available at point of polymer addition.

To cater for all circumstances, polyelectrolyte manufacturers have available a range of products that vary in terms of cationic content, molecular weight, level of cross-linking and physical form. As discussed in Section 6.7, the number of variables involved in any solid-liquid separation process means that polymer selection is far too complex to be carried out from a theoretical basis and suppliers have to resort to empirical laboratory based product-screening tests to identify the best candidate. Having said that, there are some rules of thumb that provide some guidance that assist in identifying a short-list of products for screening tests.

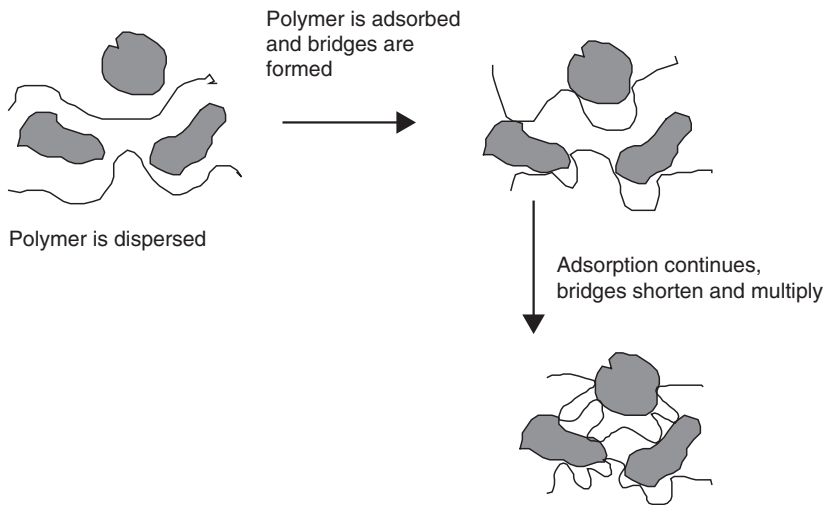
Thus:

- Increasing the ratio of secondary sludge to primary sludge increases the cationic content requirement.
- High-shear dewatering (i.e. centrifuges) often requires ultra-high molecular weight polymers.
- A medium molecular weight polymer is generally best for filter belt pressing.
- Digestion of sludge reduces particle size, which normally results in increased polymer demand.
- Maximum cake dryness can often be achieved with a partially cross-linked polymer.
- Sludges which have a high content of secondary solids (biomass) may be treated very effectively using a partially cross-linked polymer; the higher the secondary content the higher the order of cross-linking required.

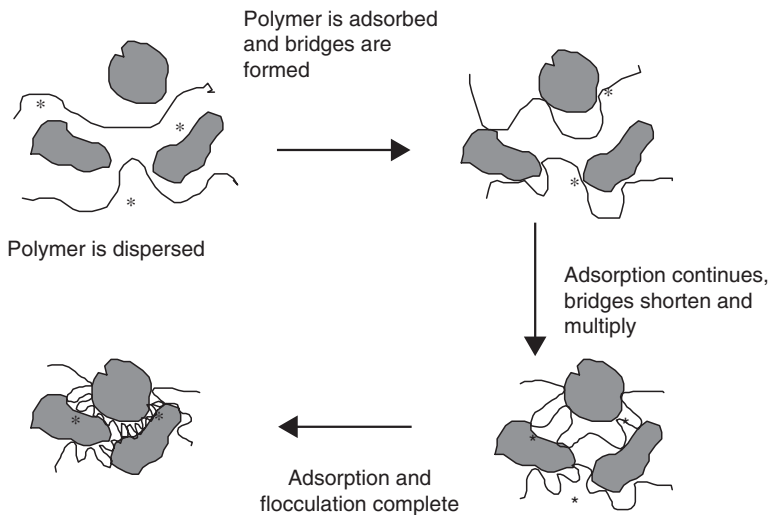
The introduction of partially cross-linked polymers, which are produced only in inverse-emulsion and liquid-dispersion form, has been a major development in the dewatering of sewage sludge [37, 38]. The polymers mix very readily into sludge yet produce large, rapidly draining flocs and ultimately much drier cakes. They produce flocs of different characteristics to those of the more conventional linear (i.e. non-cross-linked polymers), giving dewatering benefits in demanding situations. An illustration of how the flocculation mechanisms of linear and partially cross-linked polymers vary is shown in Figure 6.20.



*Conventional bridging flocculation*



*Bridging flocculation with partially crosslinked polymer*



**Figure 6.20** Representations of bridging flocculation with linear (conventional) and cross-linked polymers.

A recent development is the utilisation of thermophilic digestion processes, which operate at a temperature of 55°C as opposed to the more normal, mesophilic digestion which operates at 35°C. Sludge from this type of process has been found extremely difficult to treat, requiring high polymer doses and often the use of two polymers: a polymer

coagulant (e.g. polyamine) and a high molecular weight cationic polyacrylamide, to achieve satisfactory conditioning. [39].

## 6.10 Industrial effluents

Industrial effluents tend to be complex and vary significantly from one industry to another; consequently they must be treated on a case-by-case basis [40]. The potential impact of industrial effluents when discharged to sewer is assessed primarily by measurement of volume, COD (chemical oxygen demand) and suspended solids. Consents, or effluent standards, are normally issued by regulators for discharge to sewer [41], and these include limits on volume, COD, suspended solids and specific pollutant types, for example heavy metals, grease and oil, persistent and/or toxic organics and colour from waste dyes.

To meet the consent limits and reduce the polluting load and hazardous substances to acceptable levels, most industrial facilities carry out some form of wastewater management and treatment. The simplest form of treatment entails settlement for removal of suspended solids. In such a case, addition of a high molecular weight polyelectrolyte based on polyacrylamide as sole flocculant may be used to assist sedimentation of particles. The choice between anionic, non-ionic or cationic charge on the polyelectrolyte will depend to a large extent on the chemistry of the particles to be flocculated. Such treatment, however, will often remove only 10–30% of the COD.

Where more substantial reduction of COD is required this usually necessitates pH adjustment and precipitation/coagulation of the dissolved and colloidal pollutants prior to flocculation. Some commonly used inorganic coagulants are: lime, ferric chloride, ferric sulphate, aluminium sulphate and polyaluminium chloride (PAC). Typically used organic coagulants are the cationic polyelectrolytes: polyDADMAC, polyamine and dicyandiamide condensation resin. Combinations of inorganic and organic coagulant may also be used to advantage in many cases. After coagulation the fine, micro-flocs can be built up into rapidly settling flocs by addition of a suitable high molecular weight polyacrylamide [42, 43].

A typical industrial effluent treatment process comprises a number of stages as follows:

1. Volume equalisation
2. Coagulation
3. Flocculation
4. Settlement or DAF
5. pH adjustment
6. Discharge to sewer

The above type of process is generally referred to as physico-chemical treatment. For effluents with high dissolved organic content, such as those from the food industry, biological treatment is an important method of treatment, involving normally activated sludge plant or percolating filters. Often it is found advantageous to combine physico-chemical and biological treatments in one process train, the former being used to reduce the loading onto the latter and thus minimise plant size and energy requirements.

Table 6.1 provides varied examples of industrial effluent treatment where polyelectrolyte application has been used [44–49].

**Table 6.1** Examples of industrial effluent treatments involving application of polyelectrolyte

Industry	Effluent characteristics	Treatment process	Chemical pre-treatment
Tannery	High COD and SS, Contains oils and fats, proteins, sulphide chrome, salts	Screening, coagulation and flocculation, settlement or flotation prior to biological filter	Aluminium or ferric sulphate followed by anionic polyacrylamide
Slaughterhouse	High dissolved and colloidal COD and SS. Contains fats and protein (blood), dirt and manure	Grit chamber, screen, coagulation and flocculation, DAF	Aluminium or ferric sulphate or PAC followed by cationic or anionic polyacrylamide
Laundry	Oils, fats and greases, organics, surfactants, builders, solvents, HMs	Coagulation and flocculation, DAF and filtration	Polyamine plus ferric chloride or PAC followed by anionic polyacrylamide
Textile dyeing	Highly coloured, high COD. Contains dye residues, pigments, dispersants, sequestering agents, HMs, salts	pH adjustment, coagulation and flocculation, DAF then biological treatment	Dicyandiamide-formaldehyde resin followed by cationic polyacrylamide
Dairy	High dissolved COD and SS. Contains, proteins, fats and lactose	Biological treatment, coagulation and flocculation, and settlement	PAC followed by cationic polyacrylamide
Paint manufacture	High COD and SS. Contains pigments, resins, surfactants, dispersants, dyes, solvents	Coagulation and flocculation and settlement	Blend of ferric sulphate and polyDADMAC followed by cationic polyacrylamide
Gravel washing	High SS. Contains sand and clay particles	Flocculation and settlement	Anionic polyacrylamide
Vehicle manufacture	High COD and SS. Contains oil and grease, HMs, iron, sulphate and phosphate	HM precipitation, coagulation, flocculation and settlement	Lime, blend of ferric sulphate and polyamine followed by anionic or cationic polyacrylamide
Papermaking	High COD and SS. Contains wood fibre, cellulose, hemicellulose, lignin, tannin, phenols, fats, esters terpenes, resin	Screening, coagulation and flocculation, settlement then biological treatment	Polyamine or PAC followed by anionic or cationic polyacrylamide
Metal-finishing	Low COD and SS. Contains HMs, cyanide, oils and grease, solvents, acid and caustic	HM precipitation, coagulation, flocculation, settlement then sand filtration	Lime and sodium dithioicarbamate followed by anionic polyacrylamide
Refinery	High COD. Contains oil, phenols, ammonia, sulphides, cyanide, thiocyanate	API separator, coagulation and flocculation, and DAF	Polyamine followed by anionic or cationic polyacrylamide

SS: suspended solids; HMs: high methoxyls.

## 6.11 Potable water treatment

To produce potable water which is safe to consume and free from turbidity, colour, odour and taste natural (raw) water abstracted from rivers, lakes, reservoirs and wells, etc., must be treated to remove pathogenic organisms, and mineral and organic contaminants. This is normally done by a process train comprising coagulation, flocculation, sedimentation and filtration followed by disinfection using either chlorine or ozone.

Synthetic polyelectrolytes have been used for many years to assist the traditionally used inorganic coagulants (e.g. ferric and aluminium salts) in the coagulation and flocculation stages. Polymers typically used as partial replacement for the inorganic coagulant, and occasionally as complete replacement, are the polyDADMACs and polyamines. These highly cationic species are especially suitable for direct filtration of highly peat-stained waters and for clarification-settlement of highly turbid waters, where in both cases the reduced production of sludge is found to be beneficial.

Polymers normally used as 'coagulant aids' or 'flocculation aids', where the main purpose is to strengthen and increase the size of flocs and improve particle capture after coagulation has taken place, are the polyacrylamides of non-ionic, or low to medium cationic or anionic charge. The latter type of polymer also finds application in the dewatering of the sludges produced from clarification treatment of potable water [50].

## 6.12 Paper making applications

### 6.12.1 Retention, drainage and formation

The papermaking process uses, together with cellulose fibres as a supporting framework, materials, such as inorganic fillers (calcium carbonate both naturally occurring and synthetic, clay and titanium dioxide amongst others), starches and process and effect chemicals.

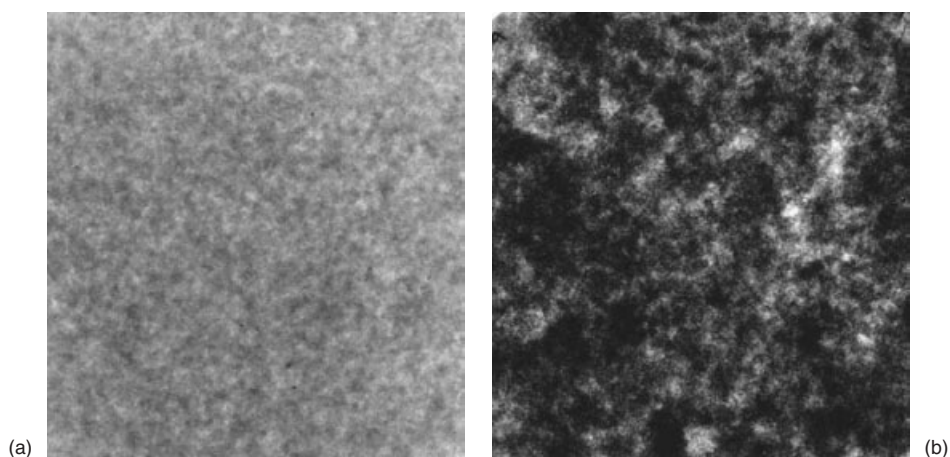
The furnish contains between 0.3% and 1.5% dry papermaking materials so for each ton of paper made between 66 and 150 tons of water need to be removed in a controlled manner.

Retention is effectively the efficiency of the paper machine. Retention can be divided into mechanical retention and chemically assisted retention. Mechanical retention is caused by both the machine wire used to form the paper web and by the wet paper web itself. Chemically assisted retention is accomplished using retention aids. These water soluble polymers bind the smaller particles like fines and fillers by various mechanisms to the fibre.

Drainage is the controlled removal of water on the wire and press section. The retention aid removes the free water within sheet interstices and capillaries between fibres and fines by flocculation.

Depending on the cationic charge of the retention aid, fibre-surface bound water can be removed via charge competition by the retention aid.

Formation is the appearance of the sheet in its final finished state. The use of retention and drainage aids significantly affects the formation of the sheet leading to a 'flocy' or uneven appearance with areas of high and low grammage. Good and bad formation is illustrated in Figure 6.21.



**Figure 6.21** Paper formation. (a) Good formation; (b) Bad formation.

Generally there is a proportional relationship between retention and drainage and an inverse one between retention and formation. For the paper industry there are serious negative implications for the overdosing of flocculants.

As a result of their effects on the paper stock, the benefits of retention aids for the paper-making process can be described as follows:

- Higher machine speeds and enhanced productivity due to superior water removal.
- Higher efficacy of paper additives like fillers, size, dyes and functional chemicals.
- Improved runnability as a result of a reduction in material circulating in the white water system.
- Reduction in the cost through the replacement of fibre with inorganic fillers.
- Decreased two-sidedness as a result of a more even filler and fines distribution in the sheet.
- Energy savings because of better drainage and less steam consumption.
- Better formation as a result of the possibility to dilute the paper stock.
- Decreased wire abrasion as a result of less vacuum needed for drainage.

### **6.12.2 Flocculation mechanisms in paper making**

The type of flocculation, and mechanism for it, is dependent on both the molecular weight and the charge of the retention aid. Several mechanisms for flocculation have been described in the literature and those covering charge neutralisation, charge patch mechanism and bridging flocculation have been described earlier in this chapter. Other mechanisms involving a number of reagents are described below.

*Complex:* A number of the more modern retention and drainage programmes use this mechanism. Usually a cationic (either modified starch, guar gum or synthetic) polymer is added first and flocculates the fines and fillers according to the bridging mechanism. After a shear stage an anionic species is added to the suspension. This can be either a colloidal

[51] or structured silica [52], a bentonite clay [53] or an anionic polymer [54] (typically highly structured) either singly or in combination [55]. Advantages of these complex flocculation mechanisms are increased retention, drainage, and formation. If the cationic component is structured (e.g. cationic starch) then the most effective microparticle is an unstructured colloidal silica, whilst for most linear cationic species a structured microparticle is superior [56].

*Network*[57]: This is based on hydrogen bond interactions and electrostatic bridging using divalent calcium ions. This is particularly effective in systems which have high levels of conductivity where ionic interactions are inadequate. Examples of this type of system include:

- Polyethylene oxide and phenolic resin (either a synthetic co factor or a naturally occurring lignosulphate)
- anionic polyacrylamide and bentonite

#### 6.12.2.1 *Application of water soluble polymers*

Cationic starch used for strength is generally added to the thickstock, at or even prior to the machine chest, to allow thorough mixing and adsorption on to the fibres.

Low molecular weight polymers (coagulants used to enhance the runnability of the paper machine are also added here).

If just a single component retention aid is used then that would be typically added just prior to the headbox to reduce the shear-induced floc breakdown. However if poor formation results from this then the addition point can be moved back to allow shear to reduce floc size.

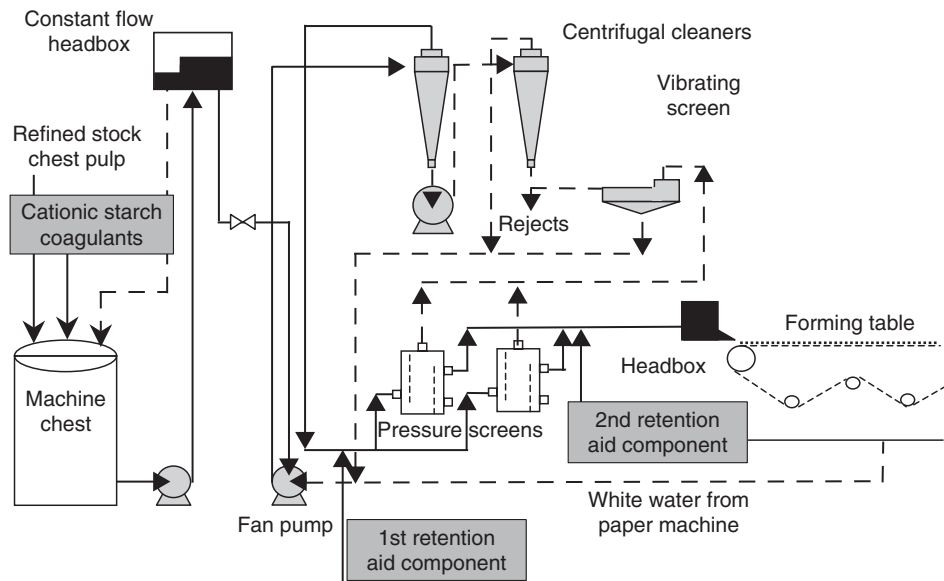
For multi-component-retention systems the cationic species is added before the screens and the resultant floc are allowed to be broken down before the anionic microparticle(s) is (are) added just before the headbox. The paper making process is illustrated schematically in Figures 6.22 and 6.23.

### 6.12.3 *Development of retention, drainage and formation programs*

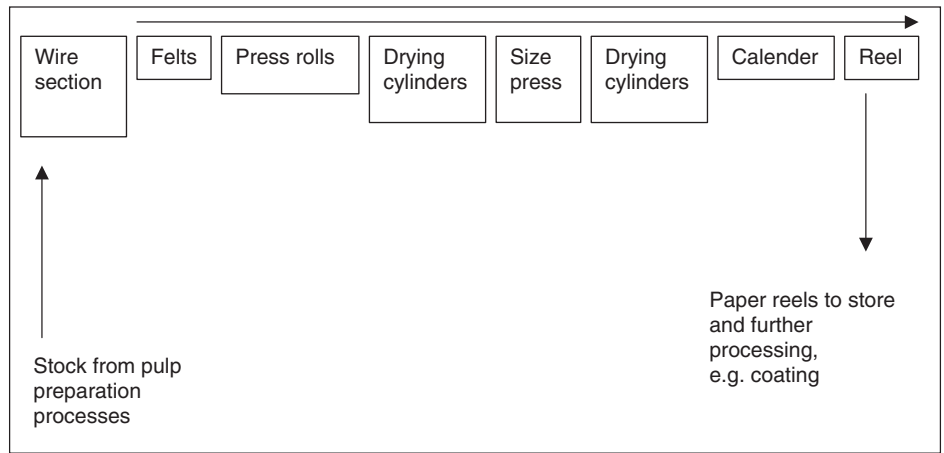
In order to fully understand the systems in use today it is useful to have an insight into the way in which the various systems have developed. Existing literature on wet-end chemistry for papermaking has developed models for different retention mechanisms and defined a common terminology that is used in the following paragraph [58, 59].

#### 6.12.3.1 *Papermaker's alum*

The introduction of compounds for retention and drainage in the paper industry began with the invention of rosin sizing through Moritz Illig 1807 in Darmstadt/Germany. Rosin size is made of tall or tree resins, which are either saponified with caustic soda or dispersed with protective colloids. The rosin size was at first fixed to fibre with potash alum, a double salt of aluminium and potassium aluminium sulphate. Later on aluminium sulphate was



**Figure 6.22** Stock approach flow diagram including water soluble polymer addition points.



**Figure 6.23** Overview of the paper making process.

used and is it is still used today for acid papermaking. Its performance is based on forming a cationically charged colloid, in which aluminium is present as polynucleic cluster. Since the active aluminium species is only present at an acid pH, its application is limited to the acid papermaking process [60] that was predominant until the first part of the 20th century. As a result of the introduction of neutral or alkaline papermaking, alum has now lost some of its importance in the paper industry. PAC has been established as an alternative for alkaline grades during the last two decades.

### 6.12.3.2 *Polyethyleneimines/polyamideamines and cationic starches*

A breakthrough for higher production capacities with faster and bigger paper machines came alongside chemical advancements with PEI/polyamideamines and cationic starches in the 1950s [61]. PEI work mainly by charge neutralisation and patching, whereas it is believed that starch primarily follows the patch mechanism together with some minor bridging. Over the years these polymer classes have been enhanced and modified so that they are still common in the industry as part of retention and drainage programs [62]. PEI, for instance, is widely used in dual cationic programs, consisting of a high molecular weight cationic polyacrylamide and a coagulant such as PEI, whereas cationic starch is often used when strength and formation is an issue.

### 6.12.3.3 *Polyacrylamides*

In the 1960s polyacrylamide powder products started to become widespread in the paper making industry [63]. Polyacrylamides have a higher molecular weight than PEI and starches, and work by bridging as the major mechanism. This enabled the papermaker to raise the filler content as well as to use recycled fibre, which contains more fines and colloidal material [64, 65]. Predominantly cationic polyacrylamides with 5–30 wt.% charge are used for paper making, although anionic polyacrylamides can also be applied, either as a single component or in dual systems in combination with cationic materials.

Early in the 1970s, polyacrylamides in the form of emulsions became available [66]. These offered easier solution preparation, particularly where make-up facilities were limited. They also offered opportunities for greater variation in molecular weights and structural modifications compared to the solid grade equivalents. Several structural modified polyacrylamide emulsion polymers have been developed since then, such as highly anionic charged, filamentary micronetwork polymers for advanced two- or three-component systems or highly linear cationic retention aid with increased molecular weight and solubility [67]. Also cross-linked and non-cross-linked organic cationic micro beads are described for the use as retention aids [68].

### 6.12.3.4 *Two-component micro particle programs*

Retention and drainage programs using an inorganic microparticle component, such as bentonite or colloidal silica, were first described in the 1980s and became more widespread in the 1990s [69–71]. They are either combined with cationic starch or a polyacrylamide type retention aid, whereby both components are consecutively added to the paper thin stock with a shear stage in between. The mechanism follows the complex flocculation model and is reversible. Microparticle programs offer the paper maker a much better balance between retention, drainage and sheet formation.

### 6.12.3.5 *Poly ethylene oxide/cofactor programs*

Since the late 1970s several papers have been published regarding the application of polyethylene oxide/cofactor [72] in highly contaminated systems. Poly ethylene oxide requires a second component, known as a cofactor in order to obtain good flocculation. Some



pulps contain a natural cofactor, whereas in most pulps the addition of synthetic cofactors is necessary. Commercial cofactors are mostly phenolic resins with sufficient charged groups to make them water soluble [73]. The predominantly proposed retention mechanism is network flocculation via hydrogen bonding and electrostatic bridging comprising divalent calcium ions [74]. Despite the quantity of research that has been carried out, polyethylene oxide/cofactor based retention and drainage programs remain niche systems, presumably due to their well-known shear and chemical sensitivity and its resultant negative impact on sheet formation.

#### 6.12.3.6 *Polyvinylformamide-polyvinylamine (PVFA-PVAm)*

Polyvinylformamides, and their products of hydrolysis, represent a relatively new class of polymers for retention, drainage and formation, which was introduced in the 1990s. The synthesis of PVAm is obtained by polymerisation of vinylformamide followed by a hydrolysis step. The degree of hydrolysis provides the unique possibility to adjust the desired ratio between molecular weight and cationic charge [75]. Depending on the molecular weight used coagulation, patching or bridging are the retention mechanisms.

#### 6.12.3.7 *Three-component retention drainage and formation programs*

At the beginning of the 21st century, RDF programs have been developed that 'decouple' retention, drainage and formation. These programs consist of a cationic high molecular weight polyacrylamide, a microparticle based on either bentonite or a structured silica and, finally, a structured, anionic micro polymer. Earlier in this section the dependency of the relationship between retention, drainage and formation was described. However, using these multi-component systems the skilled paper technologist can vary the relationship of the three components to obtain the desired retention, drainage and formation component essentially independently of each other.

### 6.13 **The use of high molecular weight flocculants in agriculture**

Soil crumbs owe their stability in part to the presence of naturally occurring polymeric materials (humus), which bind to the soil. The first synthetic polymers to improve soil structure and enhance crop growth were introduced in 1951. The results of incorporating polymers into soil were spectacular, but the dose rates required made their use uneconomical.

In the early 1980s, the first commercially successful high molecular weight soil stabilisers were introduced for the prevention of soil capping or crusting. These products were effective at significantly lower dose rates than previous synthetic polymers. In the mid 1980s these polymeric soil stabilisers were used for the first time in irrigation systems, in order to combat soil erosion.

The polymers are effective through two mechanisms, soil binding and flocculation. The polymer can bind to soil crumbs, giving structural stability. This reduces crumb breakdown on irrigation and maintains an open structure, which facilitates infiltration. This mechanism

is only moderately dependent on the molecular weight of the polymer. If breakdown does occur, the polymer will flocculate any suspended clay and deposit it on the field.

Studies have shown that high molecular weight anionic polyacrylamide polymers are most effective as soil stabilisers [76]. These polymers bind primarily to calcium ions that are in themselves bound to anionic sites on the surface of the soil crumb (a process known as calcium bridging or salt linkage). The anionic nature of the soil crumb arises due to the anionic surface charge of the clay portion within the soil.

In the practice of furrow irrigation [77] water is applied to the field via a man made ditch. The water is usually siphoned directly into the furrow and allowed to free run the length of the field. Without the use of erosion control polymers, soil losses in the order of 5–50 metric tons per hectare per season are common. The eroded soil discharged from the field often contains absorbed materials such as nutrients and pesticides that also have an environmental impact. Prior to the introduction of anionic polyacrylamides into this application control measures such as sedimentation ponds and vegetative filter strips were commonly used to contain off field soil losses. Treatment of the irrigation stream with very low levels (typically 2–10 ppm polymer or 2–10 kg/hectare polymer) of high molecular weight anionic polymer has been shown to be very effective at reducing soil movement with most soil types. Most effective control is seen with soils having a clay content greater than 10%. Soil losses are normally reduced by 90–98%, depending on soil type. This pre-treatment of furrow irrigation water has become common in the USA and Australia where solid grade products are applied directly into the irrigation stream using a variety of powder dispensers.

Overhead irrigation (such as is produced by centre pivots) is becoming increasingly common globally. Many growers prefer this practice as it is less labour intensive and gives greater control of water placement. Soil erosion is also a problem with this technique. Erosion control and water infiltration benefits have been demonstrated with the same polymers as used for furrow irrigation. Liquid formulations such as inverse emulsions are often favoured for this technique where the polymeric formulation is injected directly into the irrigation supply at the centre pivot.

More recently polymers have been incorporated directly into liquid and solid based fertilisers, thus giving farmers a greater choice of application technique for the soil stabiliser.

## 6.14 Conclusions

Polymeric water soluble flocculants and coagulants are used extensively in a wide range of industries. Their use, initially, was to provide improvements in the efficacy and speed of the separation processes. However, their widespread use and technical developments have meant that, over the years, commonplace processes that are now in use, such as centrifuge dewatering of sewage sludge dewatering and high speed paper making would not be possible at all without the addition of these reagents.

Optimum product choice is required to ensure the most efficient use of the flocculants and coagulants is made. This is accomplished through choice of chemical type, that ensures adsorption onto particle surfaces, and via modifying molecular weight and structure that is largely dependent on the separation techniques employed.

Whilst there are a number of general guidelines that can be followed, exact choice of product or system has to be carried out through empirical testing on the actual substrate under investigation.

It is anticipated that this class of chemicals will continue to find widespread use for the foreseeable future.

## Acknowledgments

The author would like to acknowledge the major contributions that have been made to this chapter by colleagues at Ciba Specialty Chemicals, namely Simon Donnelly, Brian Dymond, Andrew McCann, Michael Green, Peter Norman and Holger Reinicke.

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## Chapter 7

**Polymer Micelles: Amphiphilic Block and Graft Copolymers as Polymeric Surfactants***G rard Riess***Nomenclature**

For some polymers the abbreviations are those of the corresponding monomers, for example *MMA* methylmethacrylate with *PMMA* being the corresponding polymer.

ATRP	atom-transfer radical polymerization
BAEMA	butylaminoethylmethacrylate
BIC	block ionomer complex
CAC	critical association concentration
CMC	critical micelle concentration
CMT	critical micelle temperature
CRP	controlled radical polymerization
CSC	core-shell-corona micelles
DEAEMA	diethylaminoethylmethacrylate
DLS	dynamic light scattering
DMAEMA	<i>N,N</i> -dimethylaminoethylmethacrylate
DPAEMA	<i>N,N</i> -diisopropylaminoethylmethacrylate
EOVE	2-ethoxyethyl vinyl ether
GTP	group-transfer polymerization
HEA	hydroxyethylacrylate
HEGMA	hexaethyleneglycol methacrylate
HEMA	hydroxyethylmethacrylate
HMA	hexylmethacrylate
IPEC	interpolyelectrolyte complex
MAA	methacrylic acid
MADIX	molecular design by interchange to xanthates
MEMA	2-( <i>N</i> -morpholinoethyl) methacrylate
MM212	'methylidene malonate' (1-ethoxycarbonyl-1-ethoxycarbonylmethylenoxy carbonyl ethene)
MOVE	2-methoxyethyl vinyl ether
NIPAM	<i>N</i> -isopropyl acrylamide
NMP	nitroxide-mediated polymerization
OEGMA	oligo(ethylene glycol) methacrylate

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PAA	poly(acrylic acid)
PANa	neutralized PAA (Na counter ion)
PB	polybutadiene
PnBA	poly( <i>n</i> -butylacrylate)
PtBA	poly( <i>tertio</i> -butylacrylate)
PBLG	poly(benzyl-L-glutamate)
PBO	poly(butylene oxide)
PnBMA	poly( <i>n</i> -butyl methacrylate)
PtBMA	poly( <i>tertio</i> -butyl methacrylate)
PCEMA	poly(cinnamoyl ethyl methacrylate)
PCL	poly(caprolactone)
PDMS	poly(dimethylsiloxane)
PEA	poly(ethylacrylate)
PEC	polyelectrolyte complex
PEG	poly(ethylene glycol)
PEI	poly(ethylene imine)
PEO	poly(ethylene oxide)
PEP	poly(ethylene-co-propylene)
PI	poly(isoprene)
PIB	poly(isobutylene)
PIC	polyion complex
PLA	poly(lactic acid)
PLLA	poly(L-lactic acid)
PLGA	poly(lactic-glycolic acid)
PMA	poly(methyl acrylate)
PMANa	neutralized PMAA (Na counter ion)
PODA	poly(octadecyl methacrylate)
PPO	poly(propylene oxide)
PQVP	poly(vinylpyridine) quaternized
PS	polystyrene
PVME	poly(vinyl methyl ether)
RAFT	reversible addition-fragmentation transfer
ROP	ring opening polymerization
SANS	small angle neutron scattering
SAXS	small angle X-ray scattering
SCK	shell cross-linked knedel-like micelles
SEC	size exclusion chromatography
SFRP	stable free-radical polymerization
SLS	static light scattering
TEM	transmission electron microscopy
TEMPO	2,2,6,6-tetramethylpiperidine- <i>N</i> -oxy
VA	vinyl acetate
VBA	vinyl benzyl alcohol
VME	vinyl methyl ether
2VP	2-vinylpyridine
4VP	4-vinylpyridine



## 7.1 Introduction

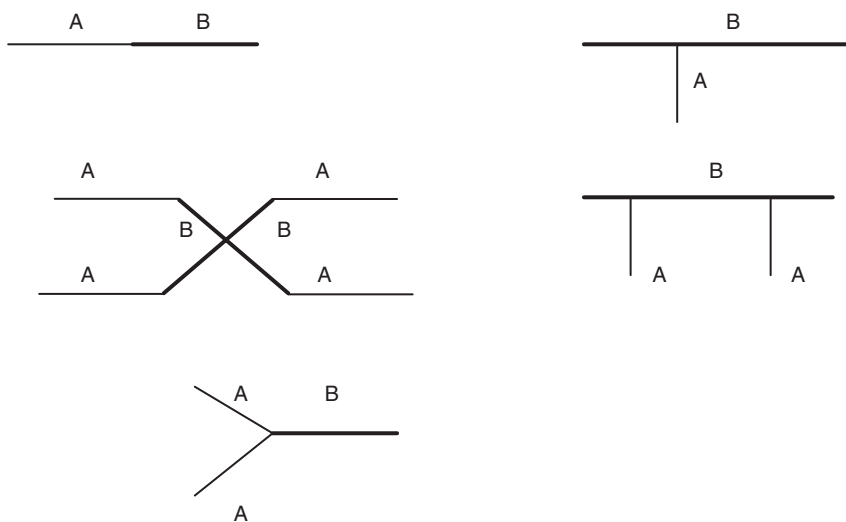
Polymer micelles in aqueous medium are typically obtained with hydrophobic–hydrophilic, so-called amphiphilic, block and graft copolymers. Analogous to conventional low-molecular surfactants, and in a selective solvent of one of the blocks, such polymeric surfactants self-assemble into nanoparticles with well-defined sizes and structures.

In fact block copolymers are generally defined as macromolecules with linear and/or radial arrangement of two or more different blocks of varying monomer composition, whereas graft copolymers are polymers comprising one or more species of blocks connected to the main chain as side chains, having constitutional or configurational features that differ from those of the main chain. The simplest structures of block and graft copolymers are given in Figure 7.1. Details of definition, nomenclature, synthesis and properties of block and graft copolymers have been reviewed previously [1, 2].

In the last decade, the synthesis techniques have been widely extended, and especially ionic and controlled free-radical methods can now be employed to prepare block and graft copolymers with well-defined compositions, molecular weights and structures of very elaborate architectures.

The increasing interest in these types of copolymers arises mainly from their unique solution and associative properties as a consequence of their molecular structure. In particular their surfactive and self-associative characteristics leading to micellar systems are directly related to their segmental incompatibility.

Thus micellization in a selective solvent of one of the blocks is a typical aspect of their colloidal properties. In fact when a block or graft copolymer is dissolved in a liquid that is a thermodynamical good solvent for one block and a precipitant for the other, the copolymer chains may associate reversibly to form micellar aggregates which resemble in most of their aspects to those obtained with classical low molecular weight surfactants. The



**Figure 7.1** Typical structures of hydrophilic–hydrophobic block and graft copolymers. A: hydrophilic block; B: hydrophobic block.

micelles consist of a more or less swollen core of the insoluble blocks surrounded by a flexible corona of soluble blocks. For dilute systems, these micelles are generally spherical with narrow size distribution but may change in shape and size distribution under certain conditions. Monomolecular micelles can even be formed with graft copolymers.

The research on the colloidal behavior of block and graft copolymers has developed gradually from a few isolated observations to a sizeable body of knowledge. The first discovery of micelle formation was apparently Merrett's [3] observation for grafted natural rubber, followed by the pioneering work of Molau in the mid-1960s [4].

Later on, the colloidal aspects mainly of block copolymers in solution have been surveyed from experimental and theoretical points of view by Price [5], Piirma [6], Tuzar and Kratochvil [7], Riess *et al.* [1], Webber *et al.* [8], Alexandridis and Hatton [9], Nace [10], Hamley [11] and quite recently by Alexandridis and Lindman [12], by Hadjichristidis *et al.* [13], by Riess and co-workers [14, 15] as well as by Xie and Xie [16] who focused their review mainly on the synthesis of block and graft copolymers containing poly(oxyethylene) segments.

In the following we intend to present an overview on some more recent results, including the author's contributions, concerning the synthesis of well-defined water-soluble block and graft copolymers, followed by the preparation and characterization techniques of micellar systems in aqueous medium, the major attention being focused on block copolymer micelles in dilute solutions. The existing theories, including those of micellization kinetics and the solubilization phenomena in micelles, will be discussed to a minor extent as these topics have been treated recently in detail [7, 8, 10–12]. An outlook will then be given on less classical micelles, such as cross-linked, ABC or mixed micelles, as well as on more complex architectures and on interpolymer complexes of block copolymers.

The last section provides a concise overview on current and potential application possibilities of block or graft copolymer colloidal assemblies as nanoreservoirs in, among others, controlled drug delivery and gene therapy.

With the increasing number of publications on these different topics, a detailed description with reference to all of them would exceed the scope of this review which has rather the purpose to highlight the background and some specific aspects of block and graft copolymer micellization in aqueous media that have appeared in the recent years.

Block and graft copolymers are mostly referred to in the following by abbreviation of their segments, such as PS-*b*-PEO for polystyrene-block-poly(ethylene oxide) and PS-*g*-PEO for polystyrene-graft-poly(ethylene oxide) or more simply PS-PEO if the type of copolymer is clearly specified. Full names of the copolymers discussed in the text are provided in the nomenclature.

## 7.2 Structures and synthesis of block and graft copolymers

The synthesis of block copolymers, mainly di- and triblock copolymers has been studied extensively and a general overview can be found in the literature [1, 13, 14, 17].

More specific topics, such as block copolymer synthesis by changing the polymerization mechanism [18], by step-growth polymerization [19], via macroinitiators [20], 'living' free-radical polymerization [21, 22] or ionic polymerization [23] were reviewed later on, as well as the synthesis of selected block copolymer types, for example hydrophilic–hydrophilic copolymers [24], copolymers based on PEO [10, 16].

The synthesis of graft copolymers with well-defined structures has not been studied to the same extent as for block copolymers. Among the review articles on this topic one could mention those of Dreyfuss and Quirk [2], Piirma [24] and Bhattacharya and Misra [25].

With the increasing number of publications in this area over the last few years, it will be impossible, in the frame of this review article, to make reference to all of them. Our attempt will rather be to outline typical synthesis strategies, mainly by 'living' polymerization and non-covalent coupling techniques, and to indicate some recent trends concerning the preparation of 'water-soluble' block and graft copolymers with well-defined structure, molecular weight and composition. A first part will be devoted to typical examples of block copolymers with linear architecture, for example di- and triblock copolymers which up to now have mostly been used in micellization studies whereas in a second part we will focus more specifically on block copolymers with more complex architectures, for example star blocks, heteroarm blocks, 'palm tree', 'double-hydrophilic' copolymers, etc. This chapter will be completed with selected examples of hydrophilic-hydrophobic graft copolymers. Additional references concerning this type of copolymers will also be provided in the other sections of this review.

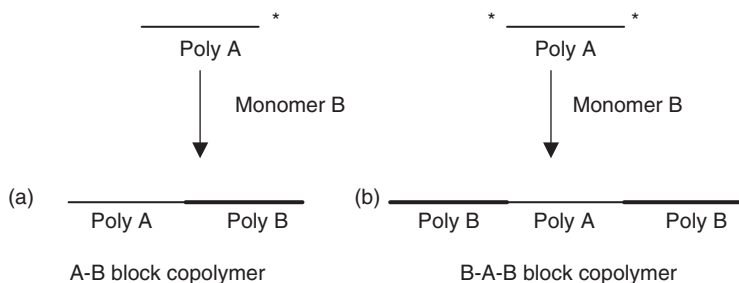
### 7.2.1 Block copolymers with linear A-B and A-B-A architecture

The polymerization methods leading to linear diblock, triblock or segmented block copolymers are based on two general reaction schemes. In a first one,  $\alpha$  or  $\omega$  active sites are generated on a polymer chain poly A which then initiate the polymerization of a second monomer B. Such a polymerization can be of free radical, anionic or cationic type and preferably of 'living type' which proceed without termination and transfer reactions. The concept of this synthesis is given in Figure 7.2.

The second method, which is usually called condensation or coupling, is a reaction or a specific interaction between chemical functional groups present at the end of different polymers.

The selection of a given synthesis technique will depend on the following criteria:

- The polymerization mechanism, for example free radical, anionic or cationic polymerization for the monomer A and/or monomer B; the most suitable case will be that where both monomers A and B are polymerizable by the same mechanism, although mechanism switching and specific coupling are at present interesting alternatives.



**Figure 7.2** Basic concept of di- and triblock copolymer synthesis.

- The structure of the copolymer, for example diblock, triblock, multiblock, star shaped, . . .
- The desired molecular weight range, knowing that condensation reactions are usually preferred for the preparation of block copolymers of lower molecular weight, for example from 1000 to about 20,000–30,000.
- The required monodispersity of each block and the purity of the end product (absence of homopolymers in a diblock or absence of diblock contaminant in a triblock copolymer).

### 7.2.1.1 Free-radical polymerization

Since the preparation of the first identified block copolymer by Melville [26] a large variety of A-B and A-B-A block copolymers were prepared by free-radical polymerization by using as well macroinitiators with active chain ends, either peroxide or azo groups, as polyinitiators, for example polyazoesters [20]. These techniques are still used at present for the preparation of different types of polyelectrolyte block copolymers, because charge-carrying monomers are in general not directly polymerizable by ionic techniques.

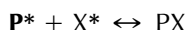
A typical example is that reported by Lieske and Jaeger [27], where poly(ethylene glycol) (PEG) macroinitiators of variable chain length were used to initiate the polymerization of alkyl substituted quaternary diallylammonium compounds.

This example demonstrates that free-radical polymerization could be the preferred mechanism for many vinyl monomers since, unlike ionic polymerization, it is tolerant of trace impurities and monomer functionality. However, one of its major drawbacks is the lack of control over the molecular weight distribution due to intrinsic termination reactions. Moreover, the efficiency factor of the initiator decreases by the so-called cage effect, for example by recombination of the primary free radicals, with increasing molecular weight of the macroinitiator [28]. This normally prevents the synthesis of block copolymers with controlled architectures, narrow molecular weight distributions and well-defined molecular weights.

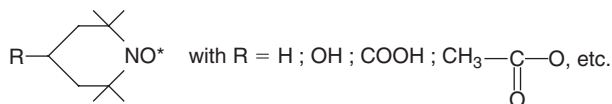
Remarkable progress in block and graft copolymer synthesis was made in recent years by so-called 'living radical' or controlled radical polymerization (CRP), which is based on the concept of reversible chain termination pioneered by Otsu and Yoshita [29].

Three basic concepts concerning 'stable free-radical polymerization' (SFRP) also called 'nitroxide-mediated radical polymerization' (NMP), 'atom-transfer radical polymerization' (ATRP) and 'reversible addition-fragmentation transfer' (RAFT) have been developed during the last decade.

The SFRP techniques involve the use of a stable radical  $X^*$  that couples with the active polymeric radical  $P^*$  and reversibly forms a dormant covalent species  $PX$ :

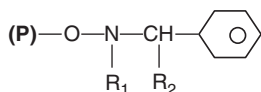


with a typical example being where  $X^*$  is a nitroxide radical such as:



The most common, with R = H is the so-called TEMPO (2,2', 6,6' -tetramethylpiperidinyl-1-oxy), which is efficient for styrene polymerization at relatively high temperatures.

As recently demonstrated by Grubbs *et al.* [30] and by Yin *et al.* [31], amphiphilic block copolymers could be prepared by NMP from alkoxyamine functional macroinitiators such as:

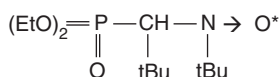


with **P** the precursor block, for example PS or PEO

$\text{R}_1 = \text{tBu}$  [30] or  $-\text{C}\equiv(\text{CH}_2\text{OH})_3$  [31]

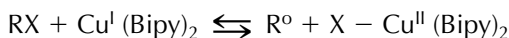
$\text{R}_2 = \text{CH}_3-\text{CH}-\text{CH}_3$

Acyclic  $\beta$ -phosphonylated nitroxides and the corresponding derivatives were developed by Farcet *et al.* [32], and later on by Dufils *et al.* [33] that are efficient at lower temperatures, not only for styrene polymerization, but also for that of alkylacrylates, acrylamides, dienes, etc. A typical example of these nitroxides is the so-called SG1 (*N-tert-butyl-N-(1-diethylphosphono-2,2-dimethylpropyl)nitroxide*) of the following structure:



A further advantage of TEMPO mediated living radical polymerization is that amphiphilic block copolymers can be prepared directly in aqueous medium as reported by Georges and co-workers [34, 35] and by Charleux and co-workers [36, 37].

The second technique of CRP is ATRP first described by Wang and Matyjaszewski [38] and by Sawamoto and co-workers [39]. This technique, since reviewed in a number of monographies and feature articles [22, 40–42] involves the reversible homolytic cleavage of a carbon–halogen bond by a redox reaction between the organic halide and a copper<sup>I</sup> halide (in the presence of a ligand, e.g. bipyridine) which yields the initiating radical and the oxidized copper complex:



As the polymer chain end still contains a halogen group, this can be used to initiate the polymerization of a second monomer for the preparation of block copolymers.

Numerous examples were reported for the preparation of A-B, A-B-A and A-B<sub>2</sub> ‘water-soluble’ block copolymers by using either sequential monomer addition or macroinitiators, for example  $\omega$  or  $\alpha, \omega$  bromine functionalized polymeric precursors [43–45].

The third CRP technique is the ‘RAFT’ method pioneered by Rizzardo and co-workers [46, 47]. The RAFT technique, as well as the MADIX process claimed by Rhodia [48] for the ‘Molecular Design via Interchange to Xanthates’, are based on the rapid and reversible chain transfer of the growing free-radical chains on dithioesters, respectively xanthates.

A typical example of block copolymer synthesis by RAFT, is that recently given by Hong *et al.* [49] who prepared PEO – b – PNIPAM with PEO capped with one or two dithiobenzoyl groups as a macrotransfer agent.

These CRP techniques, which are very tolerant to almost any functional groups and impurities, have further the advantage that a wide range of block copolymers can be obtained in a variety of solvents including in aqueous media, such as by emulsion or microemulsion processes [36, 50, 51].

### 7.2.1.2 Anionic polymerization

Anionic polymerization has been the first and the most used technique for the preparation of well-defined block copolymer. Since its discovery by Szwarc [52, 53] in 1956 a large variety of amphiphilic block copolymers were prepared [1, 14, 17]. Typical examples of hydrophilic–hydrophobic copolymers are PPO-PEO, PS-PEO and many others.

A-B structures are generally obtained by sequential addition of the monomers, either by adding directly the second monomer on the living first block, or by end-capping this first block with 1,1-diphenylethylene in order to avoid different side reactions. A-B-A structures could be obtained either with anionic difunctional organometallic initiators or by coupling the living A-B copolymer with suitable difunctional reagents, like phosgene, dihalides, esters, etc. [1]. All acrylic di- and triblock copolymers have been prepared such as PMMA-PtBA, with the interesting fact that the PtBA sequence can be easily transformed in a water-soluble PAA sequence, by elimination of isobutene from the *tert*-butyl group or by its selective hydrolysis.

A wide range of functionalized block copolymers also became available by anionic polymerization, with the specific functionality either at the junction of the A and B block, or as end-standing functionality. Of special interest for micellization studies is the functionalization of block copolymers, for example PS-PEO diblocks with fluorescent labels like anthracenyl or phenanthrenyl groups built in at the junction of the two blocks [54]. Furthermore, anionic polymerization is of special interest for the preparation of block copolymers with complex molecular architecture, as shown in the review articles of Almdal [23] and Hadjichristidis *et al.* [13].

The main limitation in the synthesis of block copolymers by anionic polymerization, is that it is applicable to a limited number of monomers and that the relative reactivity of the monomers has to be taken into account for their sequential addition. Moreover, it is generally difficult to polymerize functional monomers, for example monomers having hydroxy or amino groups, because they undergo side reactions with either the initiator or the living chain end. This problem could be solved, as shown by Hirao and Nakahama [55] by using suitable protecting groups, like *tert*-butyldimethyl silyl groups.

An important extension of anionic polymerization of acrylic monomers was the discovery of *group-transfer polymerization* (GTP), by Webster *et al.* [56], which allowed the synthesis of acrylic and methacrylic polymers in a ‘living’ reaction at ambient temperature or above. A wide range of ‘all-(meth)acrylic block’ copolymers as well hydrophilic–hydrophobic, as ‘double-hydrophilic’ copolymers which are of special interest for micellization studies, could be prepared by Armes and co workers [57].

### 7.2.1.3 Cationic polymerization

Living cationic polymerization is also finding an extensive application in the preparation of amphiphilic block copolymers. After the first examples shown by Higashimura *et al.* [58], a large variety of block copolymers based on styrene derivatives, isobutene, vinyl ethers, could be obtained as reported by Faust and co-workers [59–61], by Hadjichristidis *et al.* [13] and by Almdal [23].

Special mention should also be made for PCL-b-PEO and PEO-PEI diblocks obtained by Kim *et al.* [62] and by Riffle and co-workers [63], respectively. These typical examples where both blocks are biocompatible will be examined in more detail in Section 7.4.

### 7.2.1.4 Mechanism switching: difunctional initiators

The range of possible monomer combinations in block copolymers is greatly extended by devising processes by which the polymerization mechanism can be changed at will to suit the reactivity of the monomer being polymerized sequentially. Since the pioneering work of Richards *et al.* [64], the possibilities of monomer combinations in block copolymers have expanded by changing the polymerization mechanism. This topic has been reviewed by Riess *et al.* [1, 14], by Yağci and Mishra [18] and by Hadjichristidis *et al.* [13].

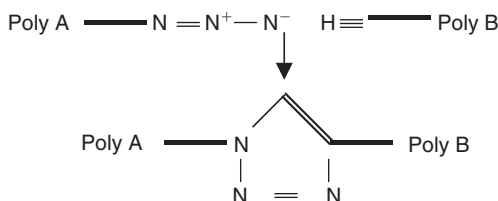
### 7.2.1.5 Coupling reactions

Numerous examples have been reported in the literature for the preparation of block copolymers by coupling end-functionalized polymers, either by direct coupling of 'living' polymers, by reacting two different polymers functionalized with suitable reactive end-groups or by using so-called difunctional coupling agents [1].

The first report concerning the direct coupling of 'living' polymers was given by Berger *et al.* [65] who investigated the reaction between an anionic difunctional polystyrene and a cationic poly(tetrahydrofuran) leading to a triblock copolymer. Mc Grath and co-workers [66] succeeded in obtaining an almost quantitative efficiency by coupling a living cationic poly(vinylether) with PMMA initiated by GTP.

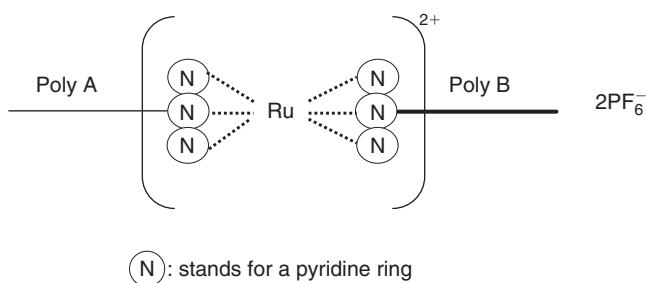
A typical example of coupling two polymers with suitable end-groups is that reported by Fock and co-workers [67]. For the industrial development of PMMA-*b*-PEO copolymers, these authors have taken advantage of the fact that the end-standing ester group of a PMMA chain, obtained by free-radical polymerization in the presence of mercaptanes as chain-transfer agents, is about 50 times more reactive than the other ester groups. Thus in a transesterification reaction of PMMA having a molecular weight below 5000 in the presence of hydroxy-terminated PEO, PMMA-*b*-PEO block copolymers are obtained in this highly selective end-group reaction.

Mention should also be made of the modular synthesis of block copolymers by the so-called 'click chemistry', designed for instance by Opsteen and van Hest [68]. These authors prepared a large variety of block copolymers via a high yield 1,3-dipolar cycloaddition coupling reaction of terminal azide and alkyne precursor blocks as illustrated in the following scheme:



In addition to covalent coupling, the non-covalent linkage of different blocks, either by metal–ligand complex formation or by selective hydrogen bonding, appeared as a recent tendency in block copolymer synthesis.

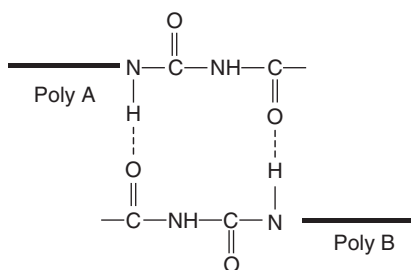
The first strategy, that of metal–ligand coordination to connect different blocks, has essentially been developed by Lohmeijer and co-workers [69, 70]. Their technique, which



**Figure 7.3** Metal–ligand coordination coupling (non-covalent coupling) of terpyridine end-functional blocks poly A and poly B (schematic representation).

consists in preparing terpyridine end-functional blocks that self-assemble through formation of ruthenium complexes, is schematically represented in Figure 7.3.

The second strategy, that of formation multiple hydrogen bonds between the chain ends of two different blocks is gaining attention in the field of block copolymer synthesis. The concept for homopolymer linking has been demonstrated by Long and co-workers [71] for uracil end-functionalized PS and PnBA. Yang *et al.* [72] extended this concept by coupling PS and PEG blocks having each aromatic oligoamide strands, with six amide groups, as chain ends. The non-covalent coupling, which is favored in bulk, was confirmed by SEC determination in DMF. This approach is schematically indicated as follows:



#### 7.2.1.6 Chemical modification of precursor block copolymers

As for homopolymers, the chemical modification of a given block, for instance by hydrogenation, halogenation, hydrolysis, etc. . . gives access to new types of copolymers such as those containing poly(vinyl alcohol) or linear PEI blocks [73, 74].

Typical examples of chemical modification leading to a wide range of hydrophobic–hydrophilic or double-hydrophilic copolymers is further the generation of PAA or PMAA blocks by selective hydrolysis of PtBA or PtBMA of block copolymers such as PS-*b*-PtBMA, PEO-*b*-PtBMA, etc. [75, 76].

#### 7.2.2 Block copolymers with complex molecular architecture

The synthesis concepts for linear structures outlined in Section 7.2.1 have been extended in the recent years to the preparation of block copolymers with complex architectures



where polymer segments of different types and different architectures are combined in the same molecule.

With the significant progress in the 'living polymerization techniques', in the design of multifunctional initiators and the control in coupling reactions a large variety of block copolymers with sophisticated architecture became available such as cyclic, H and star shaped, multiarm and 'palm-tree' or dumbbell structures, dendritic blocks linked to linear blocks, etc.

In the following typical examples of these new amphiphilic structures will be outlined, by considering at first block copolymers with poly A/poly B sequences and then those comprising poly A/poly B/poly C blocks. In both cases only copolymers having at least one water-soluble block will be considered. Further details and informations especially on star-block copolymers can be found in the excellent review articles recently published by Hadjichristidis *et al.* [13], Hirao *et al.* [77] and Quirk *et al.* [78].

#### 7.2.2.1 Block copolymers with poly A/poly B sequences

In Table 7.1 are schematically indicated several typical block copolymer structures which can be obtained by combining poly A and poly B sequences.

In a given block copolymer one can therefore combine hydrophobic and/or hydrophilic blocks, the later ones being either of ionic or non-ionic type. Of special interest in this range of block copolymers are also those comprising biocompatible or biodegradable blocks, as well as functionalized block copolymers, for example copolymers with given functional or targeting groups.

#### 7.2.2.2 Block copolymers with poly A/poly B/poly C sequences

Linear A-B-C block copolymers prepared by sequential anionic polymerization were already reported in the early 1980s [97] and were then developed systematically by Lerch [98] and by group of Armes and co-workers [99].

More complex architectures such as multiarm star-block copolymers were reported by Isono and co-workers [100] and by Dumas and co-workers [101, 102] who used as a starting point 1,1-diphenyl end-capped macromonomers. The application of 1,1-diphenyl ethylene chemistry in anionic synthesis of block copolymers with controlled structures was extensively developed by Quirk *et al.* [78] as well as by Dumas and co-workers [103].






As an alternative the multifunctional initiators developed by Sogah and co-workers [104] appeared to be as one of the most efficient routes for the synthesis of multiarm star-block copolymers.

In Table 7.2 are given the various structures of block copolymers combining in the same molecule poly A, poly B and poly C sequences, with at least one of them being water soluble.

#### 7.2.3 Graft copolymers









Conventional free-radical polymerization, either by so-called 'grafting-from' or 'grafting-onto' techniques are the oldest and were the most widely used procedures for the synthesis of graft copolymers because they are very simple [2]. In fact, graft copolymers can easily be obtained by polymerization of a monomer A in presence of a preformed polymer B acting, either as a chain-transfer agent or as a macroinitiator. However, these procedures usually

**Table 7.1** 'Water-soluble' poly A/poly B block copolymers with complex architectures: schematic structures

Structure	Type	A	B	Polymerization technique	References
	Ring diblock	PEO	PBO	Anionic	[79]
	A-B <sub>2</sub> star	PEO PLA PEO	PS PS PS	ATRP Anionic Anionic	[45] [80] [80]
	Heteroarm Star A <sub>n</sub> -B <sub>n</sub>	PS (A <sub>2</sub> ) PIB (A <sub>3</sub> ) PB (A <sub>6</sub> ) Alternating A and B blocks	PEO (B <sub>2</sub> ) PVME (B <sub>2</sub> ) PEO (B <sub>6</sub> )	Anionic Cationic Coupling	[81] [82] [83]
	'Palm tree' A-B <sub>n</sub>	PB	PEO	Anionic	[84]
	Star block (A-B) <sub>n</sub>	PEO  PhBMA PMMA PEO PCL	PS  PDMAEMA PAA PAA Poly[4- (2 hydroxy ethyl) caprolactone]	Anionic-ATRP (n = 8) ATRP (n = 3) ATRP (n = 6) ATRP (n = 3) ROP (n = 4)	[85] [86] [87] [87a] [88]



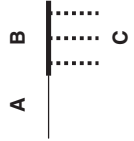
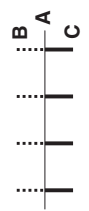
(Continued)

Table 7.1 (Continued)

Structure	Type	A	B	Polymerization technique	References
	Linear dendrimer	PEG	Poly(chloro-methylstyrene) Poly(benzyl ether)	ATRP	[89]
		PEO		Coupling	[90]
	Linear brush	PDMS	PEG methacrylic macromonomer	ATRP	[91]
		PS	PLA methacrylic macromonomer	CRP (TEMPO)	[92]
		PMAA	POE methacrylic macromonomer	GTP	[93]
	Linear dibrush	PEO	PPO methacrylic macromonomer	ATRP	[94]
	Brush-brush	PODA	PEO macromonomer	ATRP	[95]
		PEO macromonomer	PHEMA	ATRP	[96]

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**Table 7.2** 'Water-soluble' poly A/poly B/poly C block copolymers with complex architectures: schematic structures

Structure	Type	A	B	C	Polymerization technique	References
	Triblock	PB PMMA PEP PEG	P2VP PDMAEMA PEO PLLA	PEO HEGMA PHMA PLGA	Anionic GTP ATRP ROP	[98] [106] [107] [108]
	Star-block Miktoarm	PS PS	POE PMMA	PCL POE	Anionic Anionic	[103] [103]
	Graft block	PS	PI	PEG	Anionic	[105]
	Di-graft block	P(oxazoline)	P2VP	PS	Nitroxide free-radical cationic or ROP	[104]

Adapted and completed from Ref. [15]. Copyright 2003, with permission from Elsevier.

lead to heterogeneous systems with the presence of grafted and non-grafted species that would have to be separated for their characterization. Moreover, the graft copolymer is generally polydispersed in composition, molecular weight and structure, with a polydispersity in molecular weight as well for the backbone as for the grafts. It would therefore be difficult to have access to the number of grafts per backbone and to their molecular weight.

A first improvement, as shown by Rempp and Merrill [109] was the 'grafting-onto' by ionic polymerization techniques as for instance for the preparation of amphiphilic PS-g-PEO graft copolymers. Such copolymers were obtained by deactivation of a living PEO, of known molecular weight, on a partially chloromethylated PS backbone.

The use of macromonomers in controlled living polymerization techniques, such as ionic or CRP, is at present the preferred synthesis strategy for the preparation of relatively well-defined graft copolymers. Macromonomers are oligomers fitted with polymerizable end-groups, mainly styrenic or (meth)acrylic, that can copolymerize with monomers to form comb-type graft copolymers with pendent preformed polymer chains.

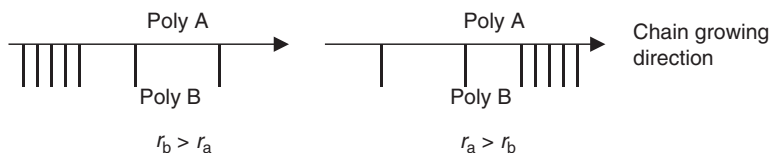
In this 'grafting through' technique, the instantaneous composition, for example the number of grafts, is governed in a first approximation by the classical Lewis–Mayo equation such as:

$$d[A]/d[B] = (1 + r_a [A]/[B]) / (1 + r_b [B]/[A])$$

In this type of copolymerization the molar feed ration  $[A]/[B]$  is usually much greater than one because the molar concentration of macromonomer is so small. Therefore the above equation is reduced to:

$$d[A]/d[B] = r_a [A]/[B]$$

If the reactivity ratios  $r_a$  and  $r_b$  are similar, one would expect a Bernoullian statistical distribution of the grafts along the backbone. Otherwise, if the reactivity ratios are quite different, there is, for conventional free-radical copolymerization, an increase in compositional and molecular weight heterogeneity with conversion. In contrast, for a living polymerization process, this situation would lead to a gradient copolymer, with a continuous change of composition along the chain. This means that the grafts may be more or less accumulated near the chain ends of the backbone polymer, depending on the relative values of the reactivity parameters. According to Neugebauer and Matyjaszewski [110], this situation can be illustrated by the following scheme:



The living polymerization techniques have the further advantage of the better control of molecular weight and that the gradient structure can be tailored by adjusting the macromonomer/monomer feed in the reaction medium.

Typical examples for the preparation of PHEMA-g-PEO and PHEA-g-PEO by ATRP have recently been given by Neugebauer and Matyjaszewski [110]. A macromonomer technique was also described by Mespouille *et al.* [111] for the synthesis of PDMAEMA-g-PCL copolymers via ROP polymerization. Amphiphilic PEO-alkyl macromonomers were recently

designed by Tenhu and co-workers [112] for the preparation of thermosensitive graft copolymers based on *N*-vinylcaprolactam.

## 7.3 Block and graft copolymer micelles in aqueous medium

It is now well established that block and graft copolymers behave as typical amphiphiles in a selective solvent, that is a 'good' solvent for one type of the blocks but a precipitant for the others. This self-assembly in organic or aqueous media, with formation of aggregates of defined characteristics, is tacitly called micellization, although the thermodynamic equilibrium conditions may not always have been reached. Thus, at a lower concentration than the critical micellar concentration (CMC), which is also designated by critical association concentration (CAC) for polymeric micelles, the copolymer molecules may have the tendency to saturate the air/solvent interface, which in turn leads to a characteristic change in the surface tension of the solvent. At a concentration higher than the CMC, the copolymer molecules aggregate reversibly to form micelles consisting of a more or less swollen core of the insoluble blocks, surrounded by a flexible fringe of the soluble blocks. If this phenomena is quite general for block copolymers, it should be mentioned that 'unimolecular micelles' can be formed in the case graft copolymers with a brush structure, for example with a high density of grafted chains.

The classical methods for the preparation and the study of block copolymer micellar systems, mostly worked out in the 1980s and beginning 1990s, have been reviewed by quite a number of authors [1, 5–12, 15] so that in the present section it will not be necessary to cover this topic in detail. Our aim is rather to outline the basic concepts and to focus on some practical informations also worked out in our group.

This section is therefore organized as follows: after a recall of the typical micellar characteristics, of the various preparation and characterization techniques, the micellization behavior of the different copolymer types, for example non-ionic, anionic and cationic types in aqueous medium will be outlined. This part will mostly be devoted to block copolymers as their structures are in general better defined than for graft copolymers.

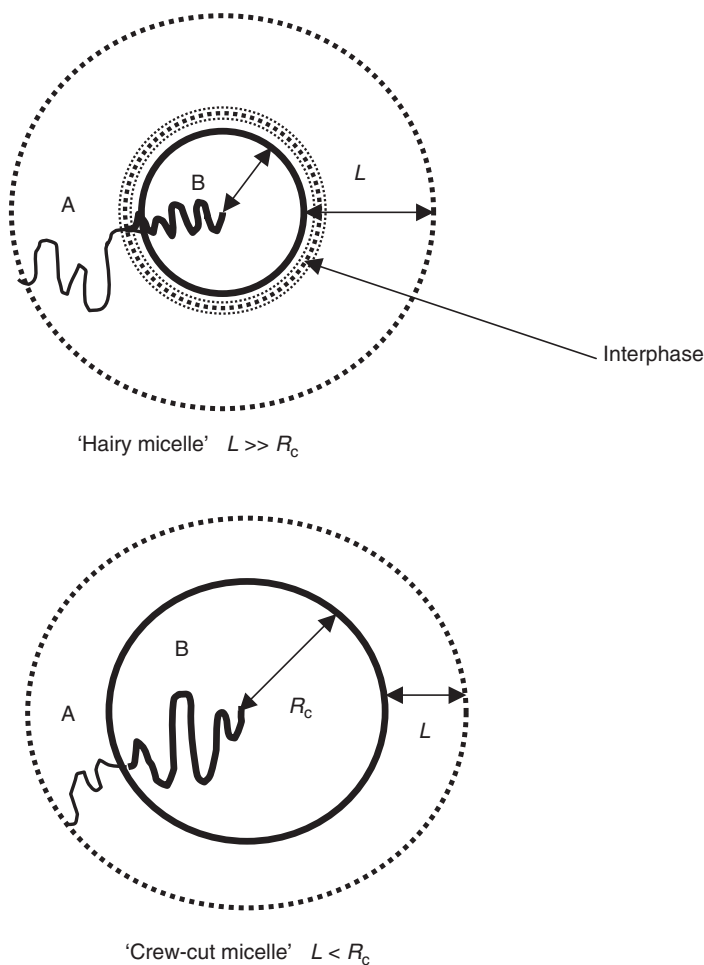
Further, the unique features of double-hydrophilic copolymers, cross-linked micelles, complex formation will be examined in the last part of this section.

### 7.3.1 Generalities

It is generally assumed that block copolymers in a selective solvent form micelles via a so-called closed association process, characterized by a certain CMC, also designated by CAC below which only molecularly dissolved copolymer is present in solution, usually as unimers. Above CMC, multimolecular micelles are in equilibrium with the unimers. This situation, analogous to classical low molecular weight surfactants is schematically represented in Figure 7.4 for a A-B diblock copolymer in a selective solvent for the A block.

Such a micellar system is characterized by:

- the equilibrium constant unimers  $\leftrightarrow$  micelles;
- the CMC and CMT, respectively the critical micelle concentration and the critical micelle temperature;



**Figure 7.4** Schematic representation of micellar structures in aqueous medium for A-B hydrophilic–hydrophobic diblock copolymers, poly A being the hydrophilic block.  $R_c$ : core radius,  $L$ : shell (corona) thickness. From Ref. [15]. Copyright 2003, with permission from Elsevier.

- the morphology which in the simplest case can be considered as spherical;
- $M^m$ , the molecular weight of the micelle;
- $Z$ , the aggregation or association number, for example the average number of polymer chains in a micelle, deduced from  $M^m$  and the molecular weight  $M^u$  of the unimer with  $Z = M^m/M^u$ ;
- $R_g$ , the radius of gyration of the micelle;
- $R_h$ , the total hydrodynamic radius of the micelle;
- the ratio  $R_g/R_h$  which is informative of the shape;
- $R_c$ , the micellar core radius;
- $L$ , the thickness of the shell (corona) formed by the soluble blocks.

### 7.3.2 *Preparation techniques*

Block and graft copolymer micellar systems are generally produced by one of the following two procedures.

In the first technique, the copolymer is dissolved molecularly in a common solvent, for example that is 'good' for both types of blocks, and then the conditions such as temperature or composition of the solvent, are changed in the way that requires formation of micelles. This is commonly achieved by adding gradually a selective precipitant of one of the block type, eventually followed by stripping the common solvent. An alternative that is often recommended is the dialysis technique by which the common solvent is gradually replaced by the selective solvent.

In a second technique, a solid sample of the copolymer is directly dissolved in a selective solvent; the micellar solution is let to anneal by standing and/or the annealing process is made by thermal treatment.

From our own experience, and also from literature, it appeared with both of these techniques, that depending on the copolymer system, an equilibrium situation is not necessarily reached, especially if the core-forming polymer has a high glass transition temperature ( $T_g$ ). In this case, for example with PS-PEO and PEO-PS-PEO di- and triblock copolymers so-called 'frozen micelles' are formed.

According to Munk [113] micelle formation by direct dissolution in a selective solvent is in general not very suitable. In fact the resulting micelles will depend on the initial two-phase morphology of the bulk sample as well as on the interactive properties of the selective solvent with respect to the polymer microphases in presence. In order to reach an equilibrium, it would be necessary that the selective solvent also swells quite extensively the insoluble block, which is almost impossible with amphiphilic block in an aqueous medium.

The stepwise dialysis technique, pioneered by Tuzar and Kratochvil [7], is therefore the preferred preparation technique for micellar systems, mainly in aqueous medium, as demonstrated by Munk [113] for PS-PMAA block copolymers and as experienced by our group for various micellar systems. Even if the formation of large aggregates can be suppressed by this technique, it does however not avoid the 'freezing-in' of a given unimer-micelle equilibrium, for example by the formation of a 'glassy' micellar core at a given temperature and/or at a specific solvent/non-solvent composition. Moreover under such conditions, the stepwise dialysis of a copolymer sample, with a polydispersity in composition and/or molecular weight, can generate a polydispersity of the resulting micellar characteristics, such as in size, in composition, in aggregation number, etc.

### 7.3.3 *Characterization of copolymer micelles: experimental techniques*

The physical methods for the characterization mainly of block copolymer micellar systems have been reviewed extensively by Tuzar [114], Munk [115], Chu and Zhou [116], Webber [117] and by Hamley [11] who have also listed systematically the different techniques which have been applied for given block copolymers. These reviews were completed



**Table 7.3** Experimental techniques for micelle characterization

Techniques	Micelle characteristics
TEM	Shape, size
SANS and SAXS	Molecular weight (weight average), $R_g$ , $R_{core}$
SLS	molecular weight (weight-average), $R_g$
DLS	$R_h$
SEC	$R_h$ , dynamics of micellar equilibrium
Ultracentrifugation	Micelle density, molecular weight (Z average), micelle/unimer weight ratio
Fluorescence techniques	Chain dynamics, CMC, hybridization of micelles
NMR	Chain dynamics
Viscometry	$R_h$ , intrinsic viscosity
Stop flow techniques	Kinetics of micelle formation and dissociation

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recently by that of Mortensen [118] and Hamley and Castelletto [118a] related to small-angle scattering techniques and that of Zana [119] dealing with fluorescence studies.

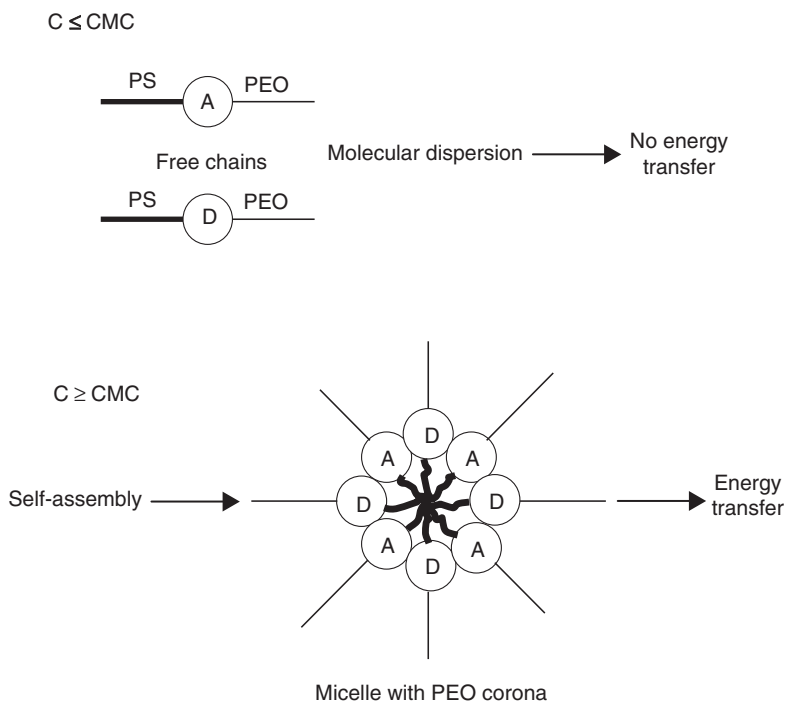
In a first approach, these characterization techniques, some of them having already been applied for several decades in micellar systems studies, can be classified in scattering, spectroscopic and in a wide range of other physical techniques which are summarized in Table 7.3 according to the listing provided by Chu and Zhou [116].

It will not be possible to cover in this section the background of all these techniques and in the following our aim is to only outline some typical aspects, such as those related to CMC, morphology, particle size and molecular weight, some encountered in our own studies, and which could be of interest for the general practice.

### 7.3.3.1 CMC

For low molecular weight surfactants, the CMC, as well as the CMT, can be determined by various scattering techniques (SLS, SAXS, . . .) by fluorescence or dye solubilization technique, by surface tension measurements, etc. . . . These techniques are also applicable to block copolymer micellar systems, however by keeping in mind that copolymers can have very low CMC values and furthermore that, due to their low diffusion coefficient, equilibrium situations are only reached after a very long time period, without forgetting that the unimer–micelle equilibrium is not attainable for ‘frozen-in’ micellar systems.

Fluorescence techniques, as outlined for instance by Zana [119] and by Jada *et al.* [120], either with ‘free’ probes like pyrene solubilization or covalently fixed fluoroprobes, might therefore be a preferred technique for CMC and CMT determinations. This concept is illustrated in Figure 7.5 for PS-PEO copolymers labeled at the junction of the two blocks with an anthracenyl as ‘acceptor’ group and a phenanthrenyl as ‘donor’ group, respectively. These two groups are capable to produce a non-radiative energy transfer above CMC, for example if they are close together in the interfacial area between core and fringe of a micelle.



**Figure 7.5** CMC determination by UV fluorescence spectroscopy: schematic representation of the donor/acceptor interaction for PS-PEO diblock copolymers labeled at the junction of their sequences with an anthracenyl (A) and a phenanthrenyl (D) group, respectively.

A typical result was obtained in our group for an equimolar blend of labeled PS-PEO diblock copolymers of same molecular weight and composition, such as:



For this system the CMC onset appears to be at 0.4 mg/l at room temperature.

This technique of covalently fixed fluoroprobes, we developed in collaboration with Winnik's group [121], is similar to that described by Webber [117]. It is not only of interest for CMC determination but also for kinetic studies of micellar block copolymer systems [122].

### 7.3.3.2 Morphology

For linear A-B and A-B-A block copolymers Price [5] has already shown in the early 1980s by transmission electron microscopy (TEM) the spherical shape of micelles, as well as their monodispersity in size distribution. This observation was confirmed by Esselink [123] and by Lam *et al.* [124] with cryo-TEM, a very valuable technique for the study of colloidal systems as demonstrated in the review article of Goldraich and Talmon [125].

Other micellar morphologies, such as slightly elliptic, rod-like, vesicles, 'crew-cut' micelles, flower-like micelles, etc. . . . were reported more recently by different authors [126, 127].

Concerning the chain conformation of the soluble A block in the micelle fringe, there is a definite difference in structure between A-B and A-B-A copolymers on the one side and B-A-B on the other. In fact B-A-B copolymers, with B being the insoluble block, have a tendency to form 'flower-like micelles' or to lead to micellar bridging.

### 7.3.3.3 Size and molecular weight

The dimensions and the molecular weight of copolymer micelles can be determined by quite a number of techniques, especially scattering and hydrodynamic characterization techniques as summarized in Table 7.3. In general practice the hydrodynamic radius  $R_h$  is determined by DLS techniques. By treating the micelles as hydrodynamically equivalent spheres and using the Stokes–Einstein relation,  $R_h$  can be evaluated from the translational diffusion coefficient extrapolated to infinite dilution  $D_o$ :

$$R_h = kT/6\pi\eta D_o$$

where  $k$  is the Boltzmann constant,  $T$  is the absolute temperature and  $\eta$  is the viscosity of the solvent.

### 7.3.4 Dynamics of micellar systems

Concerning the dynamics of block copolymers in solution, we have to consider on the one side the kinetics of micellization, which corresponds to the dynamic of the micellar equilibrium unimers  $\leftrightarrow$  micelles as well as to the problem of hybridization in micellar systems and on the other to the chain dynamics in the micellar core and in its corona.

#### 7.3.4.1 Kinetics of micellization

Kinetic studies of micelle formation and dissociation by direct methods are scarce as already mentioned by Tuzar and co-workers [7, 114] and later on by Hamley [11]. Informations can be obtained by fast reaction techniques, such as stop-flow, temperature or pressure jump techniques, as well as by steady state methods, for example ultrasonic absorption, NMR, ESR.

Stop-flow experiments have been performed by Tuzar and Kratochvil [7] and more recently by Kositzka *et al.* [128]. In analogy to low molar weight surfactants, it could be shown that two relaxation processes have to be considered for block copolymer micellar systems: the first in the time scale of tens of microseconds, associated to unimer exchange between micelle and bulk solution, and the second, in the millisecond range, attributed to the rearrangement of the micelle size distribution. Major differences were observed between A-B diblock and A-B-A triblock copolymers, which could be explained by the fact that the escape of a unimer, which has to disentangle from the micellar core, might be much easier in a diblock than in a triblock structure.

#### 7.3.4.2 Micelle hybridization

The hybridization of micellar systems corresponding to the exchange of unimers between two micelle populations of a given type of copolymer, with formation of so-called 'mixed

micelles', is a rather complex phenomenon as it is governed by thermodynamic and kinetic parameters, which in turn are very sensitive to the copolymer structures, to their molecular weights and compositions. The more, equilibrium situation might not always be reached during the whole process as a result of 'frozen micelle' formation.

This kind of problem was approached in a very systematic way by Munk [113] and Tuzar [114] by using sedimentation velocity as experimental technique. According to these authors the mechanism of hybridization consists primarily in the transfer of unimers among the micelles of both type and the driving force for this phenomenon is the increase of entropy when the two types of unimers are mixed within the micelles.

Hybridization of micellar systems was more extensively studied by fluorescence techniques. As mentioned by Webber [117], the chain exchange between micelles can be characterized by mixing micelles composed of block copolymers that are similar or identical except that they are tagged with different fluorophores. Thus, when two micelle populations, the one tagged with donor and the other with acceptor groups, are mixed and the donor is excited, primarily donor fluorescence is observed. As the chromophore tagged chains are exchanged between micelles the donor will sensitize the fluorescence of the acceptor.

A typical example of this kind of study concerned PS-(F)-PEO diblock copolymers where (F), the chromophore, is either a donor- (naphthalene) or an acceptor (pyrene) group, placed at the junction of the hydrophobic and the hydrophilic sequence. Even for relatively low molar weight copolymers no hybridization was observed at room temperature in aqueous solution. Riess and Hurtrez [129] came to a similar conclusion for PS-(F)-PEO diblock copolymer labeled with anthracenyl acceptor and phenanthrenyl donor groups, respectively.

The problem of kinetic hindrance for chain exchange is however still under debate, as reported by Winnik and co-workers [130].

#### 7.3.4.3 Chain dynamics

Scattering and fluorimetric techniques, recently reviewed by Alexandridis and Hatton [9], Procházka *et al.* [131] and by Zana [119], are excellent tools for studying the dynamics and the chain conformation in the micellar core as well as in its shell.

From these overviews it appeared that the compactness and the rigidity of the micellar core could be confirmed for different systems, however, very little seems to be known about the detailed conformation of the insoluble blocks in the core.

Informations on the chain mobility and thus on the micellar structure can further be obtained by NMR. In fact, a decreased mobility of protons in polymer chains with hindered motion causes broadening of the respective NMR lines and even disappearance of the corresponding signal when the polymer is in the glassy state as observed already in the early 1980s by Spevacek [132] and more recently by Riess and Hurtrez [129] on PMMA-*b*-PAA diblock copolymers and by Eisenberg and co-workers [133].

#### 7.3.5 Solubilization in micelles

A very useful property of micellar aggregates is their ability to enhance the aqueous solubility of hydrophobic substances which otherwise are only sparingly soluble in water. The enhancement in the solubility arises from the fact that the micellar cores, for classical low

molar mass surfactants as well as for block copolymer micelles, can serve as compatible micro-environment for water-insoluble solute molecules. This phenomenon of enhanced solubility is referred as 'solubilization'.

As pointed out by Nagarajan [134], who has recently reviewed this characteristic feature of block copolymer micelles, the solubilization in such micellar systems holds great potential for the development of aqueous block copolymer solutions as environment friendly substitutes for organic solvents and as tissue-specific drug-delivery systems. For this reason, mainly all the studies in this area are devoted to hydrophobic-hydrophilic copolymers-forming micelles in aqueous phase, such as PPO-PEO block copolymers that are commercially available in a large range of compositions and molecular weights. In addition, their biocompatibility makes them very attractive for biomedical applications.

For PPO-PEO block copolymer it could be found that the solubilization capacity of the micellar core is correlated to the Flory-Huggins interaction parameter  $\chi_{s,\text{core}}$ , which can be expressed in terms of the solubility parameters  $\delta_s$  and  $\delta_{\text{core}}$  for the solubilize  $s$  and the core-forming block, respectively:

$$\chi_{s,\text{core}} = (\delta_s - \delta_{\text{core}}) \nu_s / kT$$

where  $\nu_s$  is the molar volume of the solubilize  $s$ ;  $k$  is the Boltzmann constant;  $T$  is the absolute temperature.

### 7.3.6 Thermodynamic aspects, theories and computer simulations

In consideration of the thermodynamic aspects, and from the early results of Price [5] and Quintana *et al.* [135], it is now well established that the micellization of block copolymers in organic medium is an enthalpic driven process, the micellar core formation being the main contribution to the exothermic process.

This situation is quite opposite to that reported for the micellization in aqueous medium, for low molecular weight surfactants as well as for hydrophilic-hydrophobic block copolymers in water. Typical examples are those reported by different authors for PEO-PPO-PEO block copolymers for which the micellization is an entropy driven process [114, 135, 136]. According to Liu *et al.* [137] this phenomenon is mainly the consequence of hydrophobic interactions and changes of the water structure in vicinity of the polymer chains.

Quite a number of theories were developed over the years in order to predict, mainly for non-polyelectrolyte systems, the structural parameters of a micelle (CMC, association number  $Z$ , core radius  $R_c$ , shell thickness  $L$ , hydrodynamic radius  $R_h$ ) as a function of the copolymer characteristics, for example its molecular weight and composition. For A-B diblock copolymers which were mainly examined and where the B sequence is forming the micellar core, these characteristics are defined by the corresponding polymerization degrees  $N_A$  and  $N_B$ . In all these theories and by using various models and mathematical approaches, the total Gibbs free energy  $G^{(m)}$  of the micelle is expressed as the sum of several contributions, mainly those related to the core  $G^{(\text{core})}$ , the shell  $G^{(\text{shell})}$  and the core/shell interface  $G^{(\text{interface})}$ :

$$G^{(\text{micelle})} = G^{(\text{core})} + G^{(\text{shell})} + G^{(\text{interface})}$$

Minimization of this equation with respect to parameters characterizing the micelle leads to correlations between the copolymer and the micellar characteristics.

According to the reviews published by Tuzar and Kratochvil [7], Hamley [11], Gast [138] and recently by Linse [139], these theories are based on one side on the scaling concepts derived from the Alexander–De Gennes theories and on the other on the mean field theories first developed by Noolandi and Hong [140], Leibler *et al.* [141], Nagarajan and Ganesh [142] and by Hurter *et al.* [143]. These theoretical efforts, completed by computer simulations as demonstrated for instance by Binder and co-workers [144, 145] and by Haliloğlu and Mattice [146], have contributed to the understanding of the self-assembly of block copolymers into micellar structures. A concise overview on these topics having been given elsewhere [15], a more detailed description would exceed the scope of the present chapter. However, reference will be made to these theories in the following sections.

### 7.3.7 Micellization of non-ionic amphiphilic block copolymers

Most of the amphiphilic block copolymers of this type comprise PEO as hydrophilic block(s), whereas the hydrophobic block(s) are PPO, PBO, PS, PMMA, polyesters, etc. . . . PEO, in addition to its adjustable water solubility with temperature, has the advantage to be non-toxic and non-immunogenic, which are the requirements for biomedical applications. The expression PEG for poly(ethylene glycol) is most currently used when referring to PEO oligomers.

In this section, we intend to examine successively the micellization behavior in aqueous medium of PEO-poly(oxyalkylene), and PEO-PS block copolymers which have been studied the most extensively up to now, then that of PEO-based block copolymers with other hydrophobic blocks and finally that of block copolymers with hydrophilic non-ionic sequences other than PEO, mainly AB, ABA and BAB structures are considered at this point, whereas more elaborate block architecture will be examined in Section 7.3.12.

#### 7.3.7.1 PEO-poly(oxyalkylene) copolymers

PEO-PPO, and later on PEO-PBO copolymers, represent the link between classical low molecular weight non-ionic surfactants and polymeric surfactants. These commercially available products (formerly known as POLOXAMERS, PLURICARE, PLURONICS, SYNPERONICS), mainly with di- and triblock structures can form, depending on temperature and concentration, true solutions, micelles of different shapes and physical gels. Their micellization behavior has been studied quite extensively and the experimental as well as the theoretical results were summarized in the review articles of Nace [10], Chu and Zhou [116], Almgren *et al.* [147], Hamley [11], Booth and co-workers [79, 148] and Wanka *et al.* [149].

In the most recent ones, Booth and co-workers [79, 148] outlined the correlations between the molecular characteristics (composition, structure, molecular weight) and the corresponding micellar characteristics, such as the CMC and CMT, the micellization enthalpy, the micelle size and association number, etc. These characteristic features were studied by SLS, DLS, SAXS, SANS, NMR, etc.

By SAXS it could for instance be demonstrated that not only spherical but, depending on molecular weight, composition, temperature, concentration, salt content, also rod-like micelles are formed [116, 147]. Mortensen and Pedersen [150] have shown that in case of spherical micelles the PPO core is surrounded by a dense layer of PEO and an outer corona of flexible PEO chains.

By studying the influence of the block architecture on the micellar properties for PEO-PBO, PBO-PEO-PBO and PEO-PBO-PEO copolymers, Booth and co-workers [79, 148] came to the conclusion that at constant composition, the CMC varies as follows:

$$(\text{PEO})_m-(\text{PBO})_n \ll (\text{PBO})_{n/2}-(\text{PEO})_m-(\text{PBO})_{n/2} \leq (\text{PEO})_{m/2}-(\text{PBO})_n-(\text{PEO})_{m/2}$$

and that the aggregation number  $Z$  increases with  $n$ , the degree of polymerization of the insoluble block and is the highest for a diblock series. These trends were confirmed by Yu and Krumnov [151].

The studies on PEO-PPO, PEO-PBO di- and triblock copolymers were completed recently by Bahadur and co-workers [152] who examined the role of various additives on the micellization behavior, by Guo *et al.* [153] who used FT-Raman spectroscopy to study the hydration and conformation as a function of temperature, by Chaibundit *et al.* [154] who were mainly interested in PEO/PBO block copolymers with long PEO sequences and finally by Gente *et al.* [155] who characterized in detail the micellization behavior of PLURONIC F 68 that corresponds to a triblock copolymer PEO<sub>76</sub>-PPO<sub>30</sub>-PEO<sub>76</sub>.

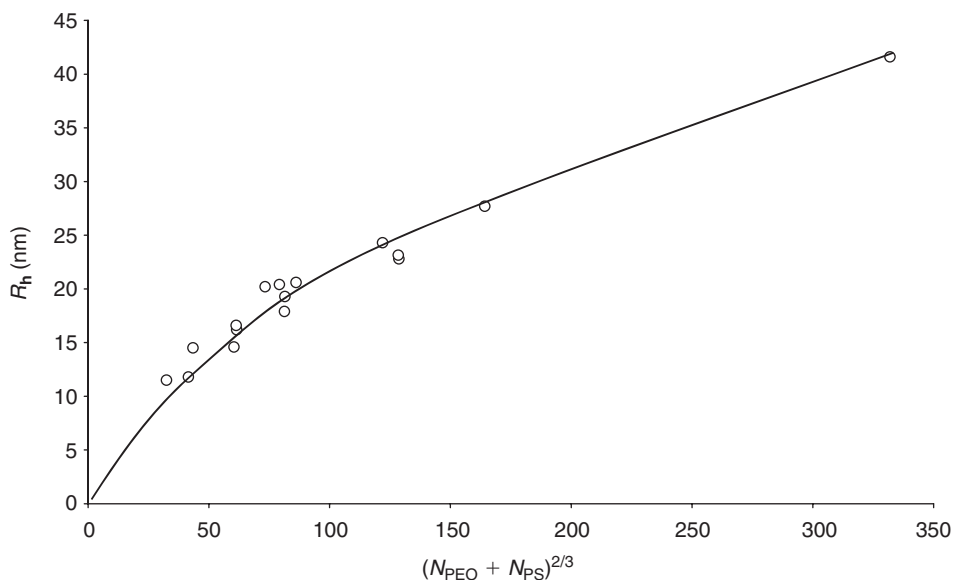
### 7.3.7.2 PS-PEO copolymers

One of the first systematic study on PS-PEO di- and triblock copolymers with controlled molecular characteristics, and in a large range of molecular weights and compositions, was reported by Riess and Rogez [156]. It could be shown that the micellar aggregation number increases with the copolymer molecular weight at constant composition and decreases with the PEO content for a given molecular weight. It was further observed that PEO-PS-PEO triblocks are less aggregated than the corresponding PS-PEO diblocks. In extension of this work, homologous series of PS-POE and POE-PS-POE with exactly the same PS precursor sequence and increasing molecular weights of the PEO block could thus be prepared [121, 122, 157, 158]. Such series of diblock copolymers were also commercially available from Goldschmidt however in a more limited range of molecular weights (e.g. 2000–7000). With respect to PPO and PBO, PS being highly hydrophobic would have the advantage to decrease the CMC for a given molecular weight of the hydrophobic blocks. However, due to the higher  $T_g$  of PS, typical non-equilibrium situations could occur, with formation of so-called 'frozen micelles' having a 'glassy' micellar core.

Some specific features will be given in the following concerning the micellization behaviors of PS-PEO and PEO-PS-PEO, studied in our group in collaboration with Winnik and co-workers [159] and with Ballauff and co-workers [160]. This type of copolymers were also examined by Yu and Eisenberg [161] especially for copolymer with high PS content, and by Khokhlov and co-workers [162].

In our approach, we were mainly interested in the micellization behavior of PS-PEO copolymers in a wide compositional and molecular weight range, for example  $5 \leq \text{wt.}\% \text{ PS} \leq 75$  and  $2000 < M_n < 100,000$ , in homologous series having the same PS precursor and in fluorescent labeled copolymers.

As an example, the hydrodynamic micellar radius  $R_h$  determined by DLS for a series of PS-PEO diblock copolymers is plotted in Figure 7.6 versus  $(N_{\text{PEO}} + N_{\text{PS}})^{2/3}$  according to the theory of Noolandi–Hong [140] where  $N_{\text{PEO}}$  and  $N_{\text{PS}}$  are the polymerization degrees of both blocks.



**Figure 7.6** Hydrodynamic radius  $R_h$  of PS-PEO diblock copolymer micelles in aqueous medium (20°C). Application of Noolandi–Hong’s theory [140] for a series of copolymers with PEO molar fractions between 0.79 and 0.95 [122].

There is definitely a trend in the increase of  $R_h$  with the total degree of polymerization, however, due to the formation of ‘frozen micelles’, neither Noolandi–Hong’s theory [140] nor that of Halperin [163] could be verified in this broad composition and molecular weight range.

This freezing-in phenomenon is also in agreement with the observation that there is almost no hybridization, for example an exchange of unimers between micelles, when two populations of fluorescent labeled PS-PEO copolymers micellar systems are mixed [129].

For a homologous PS-PEO series, having a constant low molecular weight PS block:  $N_{\text{PS}}=10$ , additional and more detailed informations could be obtained by DLS, SAXS and viscometry. These characteristics are given in Table 7.4.

From this table it appears that for a constant PS block of low molecular weight and thus of low  $T_g$  in the condensed micellar core, the CMC, the hydrodynamic radius  $R_h$  and the corona thickness  $L$  increase as expected by the different theories with increasing block length of PEO. Furthermore, the decrease of the core radius  $R_c$  and of the aggregation number  $Z$  with increasing PEO blocks is in agreement with the predictions of Nagarajan and Ganesh [142]. Finally, the ratio  $R_g/R_h$  between 0.5 and 0.7 is indicative of the spherical structure of the micelles in agreement with the results of Jada *et al.* [164].

### 7.3.7.3 Miscellaneous non-ionic copolymers

In addition to the extensively studied block copolymers based on PEO with PPO, PBO and PS hydrophobic blocks, there are quite a number of other possibilities for non-ionic copolymers



**Table 7.4** Experimental characteristics of micellar systems prepared from a homologous series of PS-PEO diblock copolymers

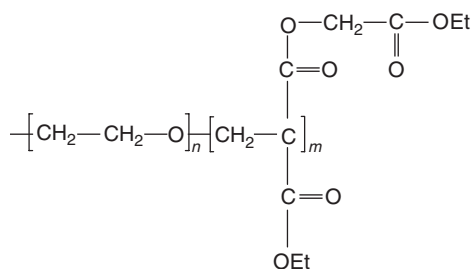
Sample	$N_{PS}$	$N_{PEO}$	CMC (mg/l)	$R_g$ (nm)	$R_h$ (nm)	$R_g/R_h$	$R_c$ (nm)	$Z$	$L = R_h - R_c$ (nm)
SE 10-10	10	23	—	6.3	8.6	0.73	5.2	370	3.4
SE 10-20	10	46	42	7.2	10.8	0.67	4.5	227	6.3
SE 10-30	10	69	64	7.9	14.3	0.55	3.6	122	10.7
SE 10-50	10	115	150	9.2	17.3	0.53	3.1	77	14.2

Adapted and completed from Ref. [15].

with A-B, A-B-A and B-A-B structures, where A is either PEO or a non-ionic water-soluble block and where B are hydrophobic blocks such as polydienes, polymethacrylates, polyesters, poly(amino acids), etc.

Typical examples of micelle formation in aqueous medium will be outlined in the following for these di- and triblock structures. Other examples of 'double-hydrophilic' copolymers or with A-B-C structures, one of the blocks being PEO will be given in Sections 7.3.10 and 7.3.12.

Micellization of polydiene copolymers was examined by Petrak and co-workers [165] in the case of PEO-PI-PEO for the development of controlled drug release systems. This interest in biomedical applications was also the starting point for extensive studies on micellar systems obtained with PEO-poly(amino acid) [166, 167], PEO-polyesters block copolymers [168, 169] and PEO-poly (ethylacrylate) [170]. PEO-poly(methylidene malonate), also designated by PEO-PMM 212, of the following structure were developed in our group:



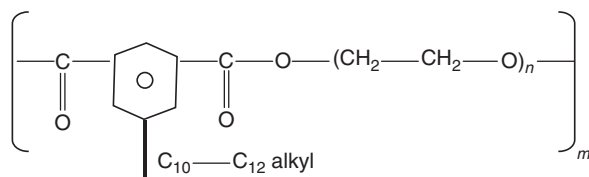
which by hydrolysis or enzymatic degradation of the ester side-groups leads to a block copolymer with two water-soluble sequences [171]. In agreement with the theory of Zhulina-Birshtein [172] it could be shown that the hydrodynamic radius  $R_h$  of PEO-PMM 212 scales as:

$$R_h/N_B^{0.6} \sim N_A^{0.6} N_B^{-0.4}$$

where  $N_A$  and  $N_B$  are the polymerization degrees of PEO and of PMM 212, respectively.

PIB-PEO block copolymers micelles studied by Kennedy [173] should finally be mentioned as the PIB hydrophobic block of very low  $T_g$  could favorize the unimer-micelle equilibrium.

Micellization of a copolymer, that may be considered as a comb-graft copolymer was studied by Watterson and co-workers [174]. This copolymer, with C<sub>10</sub>–C<sub>12</sub> alkyl side chains, synthesized through enzyme-catalyzed condensation reaction, is of the following structure:



with  $n=12, 19, 33$  and  $m$  not specified.

Concerning block copolymers with non-ionic hydrophilic block other than PEO, typical examples are those reported by Binder and Gruber [175] for poly(2-methyl-2-oxazoline)-*b*-poly(2-alkyl-2-oxazoline) and by Cho *et al.* [176] for poly(*N*-isopropylacrylamide)-*b*-poly( $\gamma$ -benzyl L-glutamate). These PNIPAM-based copolymers, are typical for the preparation of thermosensitive micelles, with a coil-globule transition of the PNIPAM fringe at around 31–32°C [177].

### 7.3.8 Micellization of anionic amphiphilic copolymers

Block and graft copolymer micelles with a polyelectrolyte corona are representative of colloidal particles which are strongly influenced by many parameters, for example by the degree of dissociation, the pH and the salt concentration, etc. These micelles provide unique colloids in which the polyelectrolyte properties can be studied at a very high segment concentration. However, the presence of electrical charges in the block or graft copolymer is adding new features to an already complex aggregation process.

Typical examples of well-defined amphiphilic anionic block copolymers are PS-PAA and PS-PMAA in the neutralized form (PS-PANa and PS-PMANa) which have been studied extensively over the last years by Tuzar [114, 136] and by Eisenberg and co-workers [127, 178] who have also recently reviewed this topic of self-assembly of polyelectrolytes. These copolymers with a PAA or PMAA sequence have been examined in a very wide compositional and molar mass range. At high pH, the (meth)acrylic blocks are ionized resulting in stable micelles with extended shell regions, due to the electrostatic repulsion of the shell-forming chains.

Typical polyelectrolyte behavior could be found for this type of micelles. Tuzar *et al.* [179] have shown for PS-PMAA the steep increase of the hydrodynamic radius  $R_h$  and of the electrophoretic mobility at a pH around 7, corresponding to the increases in dissociation of the carboxy groups when the pH was changed from 5 to 10 in various buffer solutions. In their experiments they could also demonstrate that the degree of dissociation decreases from the shell outer layer to the core-shell interface.

It was further shown by Eisenberg and co-workers [178] that by decreasing PAA/PS ratio of the blocks or by increasing amounts of salt, the morphology of the colloidal dispersion changed from spheres, to rods, to vesicles and even to more complex structures. Similar effects were recently observed by Pickel and Britt [180]. So-called 'crew-cut' micelles could

be obtained with very asymmetric block copolymers, for example those having a short coronal PANa block attached to a long core block. Further studies on PS-PAA and PS-PMAA in their acid or neutralized form were reported by Maarel *et al.* [181] who examined by SANS the structural arrangements in the micelles and by Stepanek and Prochazka [182] who determined by potentiometric titration, light scattering and fluorometry the time-dependent behavior of these polyelectrolyte micelles.

Similar studies were carried out by Wegner and co-workers [183] on fluorescent labeled PMMA-PAA copolymers in mixtures of water with organic solvents such as methanol or dioxane. From their fluorescence and NMR measurements these authors came to the conclusion that the block copolymer multimerization is preceded by the collapse of the hydrophobic block.

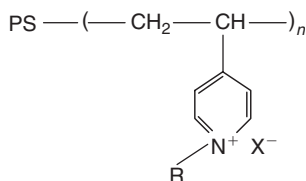
(PS-co-PAA)-b-PAA and PS-b-(PAA-co-PMA) block copolymers, with one sequence being a random copolymer, were recently examined by Laruelle *et al.* [184] and by Zhang *et al.* [185] in order to tailor the hydrophilic/hydrophobic characteristics of the micellar core or shell. Poly(perfluoromethacrylate)-PAA block copolymer micelles, studied by Ito *et al.* [186] represent in this respect an extreme case of solubility difference between core and shell.

In addition to PAA- and PMAA-based block copolymers, which are the most extensively studied systems, there are few reports concerning the micellization of copolymers with a carboxylated PS [187] or a sulfonated PI sequence [188]. For PnBA-g-PAA graft copolymers, Müller *et al.* [189] could demonstrate that at pH > 6 these polymers have high CMC values (>0.1 g/l) and predominantly form unimolecular micelles with a PnBA core and a PAA corona.

### 7.3.9 Micellization of cationic amphiphilic copolymers

The earlier studies in this area, mostly those of Selb and Gallot [190], were devoted to vinylpyridine (2VP and 4VP) containing block copolymers, readily accessible by anionic sequential polymerization and which could be transformed into water-soluble cationic species by quaternization or by simple protonation at low pH. The more recent development, pioneered by Armes and co-workers [57, 93, 191], concerns the micellization of amino-methacrylate-based block copolymers.

In fact, the first systematic micellization studies of copolymers containing cationic hydrophilic blocks were those of Selb and Gallot, who have also given a review of this topic [190]. The typical polyelectrolyte copolymers investigated by these authors were polystyrene-*b*-poly(quaternized 4-vinylpyridine) PS-PQV4P with the following structure:



with  $R = \text{CH}_3$  or  $\text{C}_2\text{H}_5$        $\text{X}^- = \text{Br}^-, \text{I}^-$

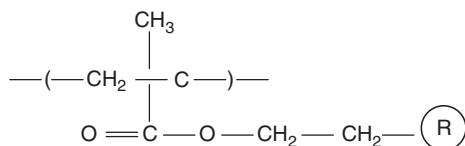
Similar to their work on anionic block copolymers, Eisenberg and co-workers [178, 192] have shown that 'crew-cut' micelles can be obtained with PS-PQ4VP of high PS content.

A typical example of the polyelectrolyte effect of quaternized PS-P4VP copolymers was reported by Calderara [126] and Riess and Hurtrez [129]. The P4VP block is soluble in methanol, whereas the corresponding quaternized block PQ4VP, obtained with methyl iodide, is soluble in water. The micellar characteristics of a diblock copolymer with  $N_{PS}=154$  and  $N_{P4VP} = N_{PQ4VP} = 381$  are given in Table 7.5.

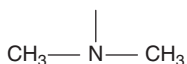
One can notice from this table that:

- the aggregation number  $Z$  is highest for PS-P4VP in methanol, whereas  $Z$  is similar for the micelles in water before and after addition of KI as electrolyte;
- the density of the micellar fringe is lowest for PQ4VP in water, which corresponds to an important stretching of the PQ4VP chains; the addition of an electrolyte such as KI leads as expected to a denser packing of the chains in the micellar fringe and to a decrease of the hydrodynamic radius  $R_h$  of the micelles.

So-called 'schizophrenic' block copolymers containing tertiary amine methacrylic sequences were developed in the recent years by Armes and co-workers [57, 93, 193, 194] and Liu and Armes [191]. They offer interesting combinations of solubility properties versus pH, temperature and electrolytes that make them very attractive for micellization studies. These authors investigated essentially the combination of four types of tertiary amine ethylmethacrylates blocks with the following structures:

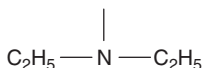


with  $R$ :



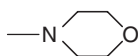
dimethylamino

DMAEMA



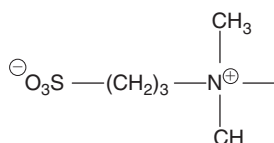
diethylamino

DEAEMA



N-morpholino

MEMA



zwitterionic substituent

**Table 7.5** Micellar characteristic of PS<sub>154</sub>-P4VP<sub>381</sub> and of the corresponding quaternized PS-P4VP<sup>+</sup> I<sup>-</sup>

	Solvent	$R_h$ (nm)	Z	$\phi$ (g/cm <sup>3</sup> )
PS-P4VP	Methanol	22.7	75	0.14
PS-P4VP <sup>+</sup> I <sup>-</sup>	Water	26.0	37	0.05
PS-P4VP <sup>+</sup> I <sup>-</sup>	Water + KI ( $7.2 \times 10^{-3}$ mol/l)	20.6	42	0.20

$R_h$ : hydrodynamic radius; Z: aggregation number;  $\phi$ : density of the corona.

Adapted from Ref. [15]. Copyright 2003, with permission from Elsevier.

These different polymers, that are water soluble at low pH or by quaternization, are interesting candidates for stimuli-responsive micelles as their solubility can easily be tuned by changing the pH, the temperature and/or the electrolyte concentration.

Hydrophilic aminoethyl methacrylate blocks can therefore be combined with various hydrophobic blocks as shown also by Jérôme and co-workers [195]. PDMAEMA-PMMA diblock and star-block copolymers, quaternized on the PDMAEMA block with different alkyl halides were synthesized by these authors who could demonstrate that with short alkyl halides the diblock copolymers behave like classical amphiphiles on micellization, whereas their behavior becomes similar to polysoaps in the case of long alkyl halides.

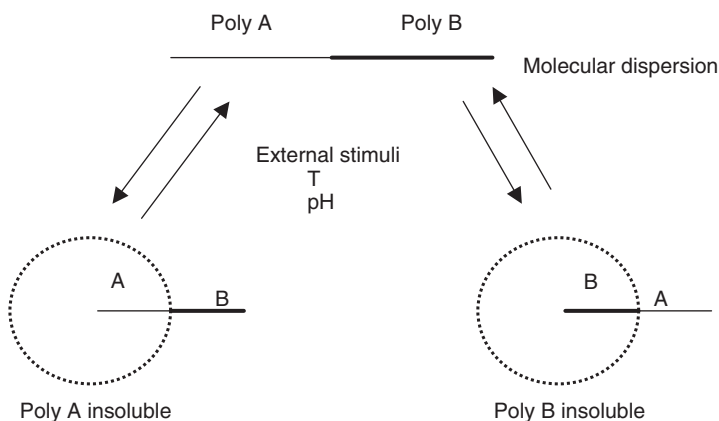
The particular interest of the strategy developed by Liu and Armes [191] is that a new category of stimuli-responsive hydrophilic–hydrophilic block copolymers becomes available for micellar studies as outlined in the following section.

### 7.3.10 Micellization of double-hydrophilic copolymers

Hydrophilic–hydrophilic also called double-hydrophilic block copolymers, consist of water-soluble blocks of different chemical nature. In aqueous solution they behave as unimers like classical polymers or polyelectrolytes, whereas their amphiphilic characteristics, such as surface activity and micelle formation, only appear under the influence of a given external stimuli, mainly temperature, pH or ionic strength changes. Micellization of these copolymers can further be induced by complex formation of one of their blocks, either by electrostatic interaction with oppositely charged polymers, by hydrophobic interactions such as with surfactants, or by insolubilization in the presence of metal derivatives. These polymer intercomplexes, mainly polyion complexes (PIC), with their application possibilities will be outlined in more detail in Section 7.3.13.

The general concept of stimuli induced micellization is schematically represented in Figure 7.7, which shows that for a given water-soluble copolymer A-B, micelles with a poly A or a poly B core can be formed.

Among the first examples of double-hydrophilic block copolymers leading to micelle formation by pH change and metal complexation, one could mention that of protonated P2VP-PEO developed in our group by Ossenbach-Sauter [196]. Although numerous examples concerning the synthesis of this category of block copolymer were reported, only relatively few before the beginning of the 1990s, were characterized by their micellization behavior. Their interest as colloidal systems has however dramatically increased in the last



**Figure 7.7** Reversible micellization of hydrophilic–hydrophilic diblock copolymers under the influence of external stimuli, for example temperature, pH, electrolyte, etc. (schematic representation).

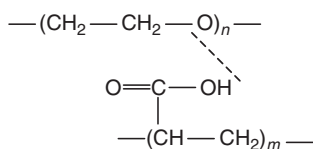
decade as shown by Cölfen in a recent review article [213]. A very systematic overview, including the synthesis techniques, the properties and the application possibilities of these copolymers has been published by this author. The following will therefore be limited to an outline of the micelle formation of these double-hydrophilic block copolymers by considering, mainly for A-B diblock copolymers, the various combinations of non-ionic, anionic and cationic blocks.

Typical examples of water-soluble block copolymers containing at least one non-ionic sequence are listed in Table 7.6.

It can be noticed that the majority of copolymers in this category contain a PEO or a PVME sequence and that for completely non-ionic systems micellization is mainly induced by a temperature change. For those copolymers with an ionic and a non-ionic sequence micellization becomes also possible by pH changes or by addition of electrolytes.

A second category of water-soluble block copolymers are those comprising two ionic sequences, either of the same type, for example anionic/anionic or cationic/cationic, or those of polyampholite types where one sequence is of anionic the other of cationic type. The corresponding examples are listed in Table 7.7.

Within the first category, that non-ionic/ionic systems, PEO-P(M)AA is one of the most extensively studied. It has the particular feature of a polyelectrolyte, due to the P(M)AA sequence, in addition to the fact that PEO in aqueous medium has a lower critical solution temperature (LCST) which depends mainly on the pH and the concentration of electrolytes. Moreover it is well established that at low pH, PEO and P(M)AA interact strongly by hydrogen bonding, with formation of a hydrophobic interpolymer complex such as:



**Table 7.6** Stimuli-induced micellization of hydrophilic–hydrophilic A-B diblock copolymers comprising at least one non-ionic sequence

A block	B block	Type (B block)	Stimulus	References
EOVE	MOVE	Non-ionic	T	[197]
VME	VA	Non-ionic	T	[198]
EO	NIPAM	Non-ionic	T	[199]
VBA	OEGMA	Non-ionic	pH	[200]
OEGMA	MAA	Anionic	Electrolyte, pH	[82]
EO	Vinylbenzoate	Anionic	pH, T	[201]
EO	MAA	Anionic	Cationic surfactant	[202]
			pH	[203]
EO	2VP	Cationic	pH	[196, 204]
EO	DMAEMA	Cationic	T, pH	[205]
	DPAEMA			
PO	DEAEMA	Cationic	T, pH	[206]

**Table 7.7** Stimuli-induced micellization of hydrophilic–hydrophilic A-B diblock copolymers comprising two ionic sequences

A block	B block	Type	Stimulus	References
DMA EMA	DEA EMA	Cationic/cationic	pH	[207]
DMA EMA	DEA EMA or DPA EMA	Cationic/cationic	pH, T, electrolyte	[208]
Vinylbenzyltrimethyl- ammonium chloride	<i>N,N</i> -dimethyl vinylbenzyl amine	Cationic/cationic	pH	[209]
MAA	4VP	Zwitterionic	pH	[210]
MAA	DMA EMA	Zwitterionic	pH	[211]
PS sulfonate	PS COONa	Anionic/anionic	pH	[209, 212]

These complexes are in addition becoming intramolecular as shown by Mathur *et al.* [214] for a graft copolymer with a PMAA backbone and short PEG grafts. Intramolecular complex formation was confirmed by Jérôme and co-workers [215] for a PMAA<sub>21</sub>-b-PEO<sub>177</sub> block copolymer, which leads in the pH range of 1–6 to micelles with a hydrodynamic radius of 50–60 nm. The core of these micelles, formed by the hydrophobic PMAA/PEO complex, is stabilized by a fringe of PEO which is in excess with respect to PMAA. At pH  $\geq 6.1$ , with increasing ionization of the PMAA block, the block copolymer is molecularly dispersed in the aqueous medium.

Systematic studies in this area were further reported by Tenhu and co-workers [216, 217] for more ‘equilibrated’ copolymers, for example PMAA<sub>122</sub>-b-PEO<sub>113</sub> and PMAA<sub>294</sub>-b-PEO<sub>113</sub>. By different techniques and especially by fluorescence spectroscopy, these authors could demonstrate that PMAA/PEO complexation occurs at pH  $\leq 2$  with formation of large aggregates. In the pH range of 3.5–6.5, micelles are formed with  $R_h$  from 8 to 45 nm depending on the ionic strength of the medium.

If the micelle formation at low pH by complexation is now well established, the situation has not yet been cleared at pH  $\geq 6$ . In fact, Jérôme and co-workers [215] detected molecularly

dispersed systems, whereas Tenhu and co-workers [216, 217] observed the presence of colloidal particles of 8–10 nm, at pH 9 and in the presence of electrolytes such as NaCl or NaNO<sub>3</sub>. The existence of colloidal systems at high pH could also be demonstrated in our group [218] and by Armes and co-workers [219] for diblock copolymers having a PMAA block and a brush sequence of PEG.

Even if no complete explanations are available to account for these discrepancies, one may postulate that the solubility of the PEO blocks might be strongly influenced by the ionic strength not only of the aqueous medium, but also to that induced by the ionized PMAA sequences in close contact to the PEO block.

The self-association of double-hydrophilic copolymers of (meth)acrylic acid and PEO has recently been extended to PEO-b-P(EA-co-MMA) [220] and to triblock brush structures [221].

PNIPAM is a well-known thermosensitive polymer having in aqueous medium a coil-globule transition at 30.9°C. Below that LCST the polymer is soluble, whereas phase separation takes place when the temperature is raised above the LCST.

PNIPAM copolymers have been investigated by many authors as they attracted interest in drug-delivery systems. Thermosensitive micelles are obtained for PEG-PNIPAM block copolymers as shown by Feijen and co-workers [222] and later on by Motokawa *et al.* [223], Nedelcheva *et al.* [224] and Hennink and co-workers [225].

Of special interest are also block copolymers based on tertiary amine methacrylates studied in a very systematic way by Liu and Armes [191], Weaver and Armes [226]. In addition to the examples already given in Section 7.3.9, these authors have developed a wide range of water-soluble block copolymers containing two different tertiary amine methacrylate sequences, for example methacrylates with dimethylamino (DMA), diethylamino (DEA) and morpholino (M) substituents, which lead under proper stimuli conditions (pH, electrolytes, temperature or combinations of these parameters) to reversible micellar systems.

### 7.3.11 Cross-linked micellar structures

Although micelles are stable in time at fixed conditions, their characteristics depend for a given system on the thermodynamic quality of the solvent and on temperature. For this reason it is impossible to study that system under different conditions, for example in a different solvent, at a different temperature or at various concentrations. The idea of Prochazka and Baloch [227] and of Tuzar *et al.* [228] to circumvent this problem was to stabilize micellar structures by cross-linking of the micellar core, either by UV or fast electron irradiation. The unimer remaining in the system after cross-linking can easily be removed by fractional precipitation or dialysis.

Systematic studies on photo-cross-linking block copolymer micelles, with a core of poly(cinnamoyl ethyl methacrylate) (PCEMA) were published by Liu and co-workers [229]. With PAA as the shell-forming block, these authors could demonstrate by SLS, DLS, TEM and SEC that photo-cross-linking of PCEMA locked in the initial structure of the micelles without any significant change in their aggregation number and size distribution. Core-cross-linking of PEO-PMAA micellar systems with Ca<sup>++</sup> ions has recently been described by Kabanov and co-workers [230].



The other possibility, at first examined by Wooley and co-workers [231, 232] is to cross-link the corona of the micelles. These kinds of nanoparticles are designated by shell cross-linked 'knedel-like' (SCK) micelles by these authors. Wooley *et al.* have applied this concept to a large variety of block copolymers, mainly hydrophobic–hydrophilic copolymers with PAA or quaternized PVP as the water-soluble block, which can be chemically cross-linked in their micellar form. A similar approach has been described by Armes and co-workers [233] for the synthesis of shell cross-linked micelles where core and shell are both hydrophilic.

### 7.3.12 *Micellization of copolymers with complex molecular architecture*

The influence of the architecture of block and graft copolymers on micelle formation was usually limited to comparisons of A-B, A-B-A and B-A-B di- and triblock linear structures in a selective solvent of A. Among the large variety of A-B block and graft copolymers with non-linear structures, as outlined in Section 7.2, only few of them have been studied, and that mainly in organic medium, with respect to their micellization behavior. The general observed trend, as for instance demonstrated by Pispas *et al.* [234] for PS-PI copolymers in organic medium, is that star architectures, for example A-B<sub>2</sub>, A-B<sub>3</sub> and A<sub>2</sub>-B<sub>2</sub> structures, have higher CMC values and thus less tendency to micellization than the corresponding linear block copolymers. As a further general rule it appeared that graft copolymers with many branches form unimolecular micelles in selective solvents of the branches, whereas in selective solvents of the backbone, one assists in the formation of plurimolecular micelles, generally with lower aggregation numbers than for comparable diblocks.

A-B-C block and graft copolymers, with three different blocks, have also attracted increasing attention because they display in the solid state a large variety of mesomorphic structures with interesting bulk properties [235, 236]. Their synthesis is well documented, however the study of their colloidal properties, and especially their micellization behavior in aqueous medium, has just been started in the last few years.

In the following, typical examples of these recent studies will be discussed, with the focus on the micellization of 'water-soluble' A-B copolymers with non-linear architectures as well as of A-B-C copolymers having at least one hydrophilic block.

The problem of condensed monolayers formation and surface morphologies of these copolymers, which has recently been treated by Tsukruk and co-workers [237] would exceed the scope of this review.

#### 7.3.12.1 *Non-linear A-B block structures*

Concerning the micellization of non-linear A-B structures it appeared from the study of Booth *et al.* [79] that micelle formation of cyclic PEO-PBO copolymers is favored over that of its corresponding linear precursor PEO-PBO-PEO triblock.

Yun *et al.* [238] investigated the aqueous solution properties of amphiphilic linear and star-block copolymers A<sub>1</sub>B<sub>1</sub>, A<sub>2</sub>B<sub>2</sub>, A<sub>3</sub>B<sub>3</sub> and (AB)<sub>3</sub>, where A is PIB and B is PVME. The CMC measured by fluorescence spectroscopy at 20°C increased in the order:

$$(AB)_3 = A_1B_1 < A_2B_2 \cong A_3B_3$$

with aggregation numbers in the range of 4500–5600.

Y-shaped double-hydrophilic block copolymers, with a poly(EO-co-PO) sequence and two blocks of various hydrophilic methacrylic polymers, were synthesized by an elaborated ATRP technique by Armes and co-workers [239]. pH and thermal stimulus-responsive micelles could be obtained by these authors.

A typical example of micelle formation with a PS<sub>6</sub>-PAA<sub>6</sub> ionic star-block copolymer is that described by Zubarev and Teng [240]. The unique feature of their copolymer, with  $M_w=35,000$ , is that the arms are not randomly linked to the core, but as six pairs of PS/PAA blocks linked to a central core.

### 7.3.12.2 A-B-C block structures

With respect to amphiphilic diblock copolymers, A-B-C triblock copolymers have the advantage to form more complex nanostructures, such as well-defined core-shell-corona (CSC) micelles, worm-like micelles, etc.

One of the first examples might be that of Patrickios *et al.* [241] who demonstrated the micelle formation as a function of pH for a polyampholyte triblock copolymer consisting of PDMAEMA-PMMA-PMAA prepared by GTP polymerization, followed by the work in our group on PB-P2VP-PEO prepared by sequential anionic polymerization [98].

Patrickios and co-workers [99, 106] extended their study by preparing the three equimolar structures A-B-C, A-C-B and B-A-C, with one hydrophobic PMMA sequence, and two hydrophilic sequences PDMAEMA and poly[hexa(ethylene glycol) methacrylate] (HEGMA) or PMAA, respectively, each of these sequence having a polymerization degree of about 10–12. For these series of copolymers, it could be shown, for instance by aqueous GPC, that the sequence arrangement has a profound effect on the self-assembly behavior and on the micelle size.

Armes and co-workers [242, 243] have also extended their pioneering work on aminoacrylate-based block copolymers to micellar studies of A-B-C copolymers such as PEO-PDMAEMA-PDEAEMA and PEO-PDMAEMA-PBAEMA in which the central PDMAEMA block was cross-linked by a difunctional alkyl iodide. For PEO-PHEMA-PDEAEMA, in view of biomedical applications, this cross-linking could preferably be achieved with divinyl sulfone, that reacts selectively with the hydroxylated PHEMA block.

In our group we became interested a few years ago in A-B-C block copolymers able to form micelles in organic as well as in aqueous medium, with the practical goal to develop 'universal' pigment dispersants, for example copolymers that are efficient as dispersants and stabilizers for pigments in aqueous and organic medium [98]. The study was focused on PB-P2VP-PEO triblock copolymers and their micellization behavior was examined in water and in heptane, which are selective solvents of PEO and PB, respectively, whereas P2VP is insoluble in both of these solvents.

The composition domain could be determined where micellization was possible in aqueous medium. For a given copolymer, micelles can be formed in water and in heptane, with less than 1% larger aggregates, if its PEO and PB contents are at least 20 wt.%.

The micellar characteristics as determined by DLS and viscometry in aqueous medium are summarized in Table 7.8.

As a general trend it can be noticed that the hydrodynamic radius  $R_h$  and the corona thickness  $L$  of the micelles increase with the polymerization degree of the PEO block. The

**Table 7.8** Micellar characteristics of PB-P2VP-PEO triblock copolymers in water at 20°C

Sample	$R_h$ (nm)	$[\eta]$ (cm <sup>3</sup> /g)	Z	L (nm)
PB <sub>100</sub> -P2VP <sub>100</sub> -PEO <sub>104</sub>	22.5	13.69	256	14.0
PB <sub>89</sub> -P2VP <sub>145</sub> -PEO <sub>125</sub>	24.0	12.12	281	15.6
PB <sub>37</sub> -P2VP <sub>115</sub> -PEO <sub>241</sub>	27.3	14.47	359	20.5
PB <sub>30</sub> -P2VP <sub>50</sub> -PEO <sub>270</sub>	26.9	16.91	382	20.3
PB <sub>131</sub> -P2VP <sub>219</sub> -PEO <sub>322</sub>	38.6	11.50	712	25.5
PB <sub>66</sub> -P2VP <sub>69</sub> -PEO <sub>356</sub>	37.1	22.86	504	27.3

Samples organized with increasing DP of the water-soluble PEO block.  
 $R_h$ : hydrodynamic radius; Z: aggregation number; L: calculated corona thickness;  $[\eta]$ : intrinsic viscosity.

aggregation number Z, however, is influenced by the block lengths of the hydrophobic PB-P2VP blocks as well as by the hydrophilic PEO block.

The theories developed in recent years to predict the micellar characteristics as a function of the block copolymer parameters concern almost exclusively A-B and A-B-A copolymers. Our intention was therefore to verify if the classical theories for A-B diblock copolymer are applicable to our PB-P2VP-PEO copolymers by considering that in aqueous medium such a copolymer has:

- a hydrophilic sequence of PEO with  $N_{PEO}$  monomer units;
- a hydrophobic moiety comprising the PB and the P2VP blocks with  $N_{PB}$  and  $N_{PVP}$  monomer units, respectively, in such a way that the total number of hydrophobic units  $N_B$  is given by  $N_B = N_{PVP} + N_{PB}$ . Furthermore, in order to take into account the difference in molar volumes of the vinylpyridine and butadiene units as suggested in the theory of Nagarajan and Ganesh [244], the number of hydrophobic monomer units has been ‘normalized’ with respect to the vinylpyridine monomer units. The total number of hydrophobic units is therefore given by:

$$N'_B = N_{PVP} + 0.65 N_{PB}$$

where the correcting factor is calculated from the respective densities  $\varphi(PB) = 0.89 \text{ g/cm}^3$  and  $\varphi(PVP) = 1.13 \text{ g/cm}^3$ .

According to Noolandi–Hong [140], the theoretical scaling laws should be as follows:

$$R_h \sim N^{0.68} \qquad Z \sim N^{0.90}$$

with  $N = N_{PB} + N_{PVP} + N_{PEO}$ .

The experimental values are in close agreement, the scaling exponents being 0.68 for  $R_h$  and 1.08 for Z.

Jérôme and co-workers [245, 246], also interested in PVP-based copolymers, have demonstrated that PS-P2VP-PEO as pH-responsive micellar systems are able, on the one side, to solubilize PS homopolymer of low molecular weight in the micellar PS core, and on the other side, to form interpolymer complexes between the P2VP block and additional PAA homopolymer. The large variety of A-B-C micellar structures, including vesicles, worm-like and

ring structures, multicomponent and cross-linked morphologies, was further illustrated by different authors [247–251].

Finally, it is worthwhile to mention that PS-[Ru]-PEO or PEO-poly(ferrocenylsilane) copolymers obtained by non-covalent coupling (see Section 7.2.1.5), and which can be considered as A-B-C linear copolymers, form stable micellar aggregates in aqueous solution, even at extreme pH values [70, 252].

### 7.3.12.3 Graft and brush structures

Micelle formation with amphiphilic graft and comb copolymers has received much less attention than that of block copolymers, although brush structures are gaining interest, mainly for biomedical applications (see Section 7.4). As already mentioned in Section 7.2, this is mainly due to the fact that these branched copolymers are not as well defined in structure, composition and molecular weight as the corresponding block copolymer, even if they are synthesized by controlled polymerization and macromonomer techniques.

Our purpose is therefore in the following to illustrate with typical examples the large variety of amphiphilic and hydrophilic–hydrophilic branched structures recently described in the literature (see Table 7.9).

One can notice from this table, that these copolymers are usually synthesized with PEG as water-soluble sequences and other biocompatible blocks such as PCL, poly(phosphazene), etc.

From the listed studies, it further appears that these graft and brush structures have overall similar properties as block copolymers such as low CMC values, pH and/or temperature stimuli response, particle sizes in the range 10–100 nm, etc.

**Table 7.9** Micellization of graft and brush structures

General structure	Backbone	Graft or brush type		References
		Hydrophobic	Hydrophilic	
Graft	Poly(vinylcaprolactam)	–	Alkyl PEO	[112]
Graft	PDMAEMA	PCL	–	[111]
Bigraft	Poly(alkylmethacrylate)	C <sub>12</sub>	PEG	[253]
Bigraft	Poly(phosphazene)	Ethyl-4-aminobenzoate	PNIPAM	[254]
Bigraft	–	PCL	PEG	[255]
Block-graft	PEO-POP-PEO triblock	–	Poly(vinyl pyrrolidone)	[256]
Brush-linear-brush (A-B-A)	B = PS	–	PEG	[257]
Brush-block-brush	–	Poly(octadecyl acrylate)	PEG	[95]
Brush-block-brush	–	–	PEG PHEMA	[96]

### 7.3.13 Comicellization and complex formation

The complex formation by polymer–surfactant interaction has been extensively studied, as well for ionic and non-ionic polymers as for the different surfactant types, for example anionic, cationic and non-ionic low molecular weight surfactants. The driving forces for these complex formations are in general electrostatic or hydrophobic–hydrophobic interactions between polymer and surfactant. These concepts have been extended to block copolymer systems mainly to those containing a water-soluble PEO block, such as PPO-PEO, PS-PEO, PEO-PMAA, PMMA-PEO in the presence of anionic or cationic surfactants [258].

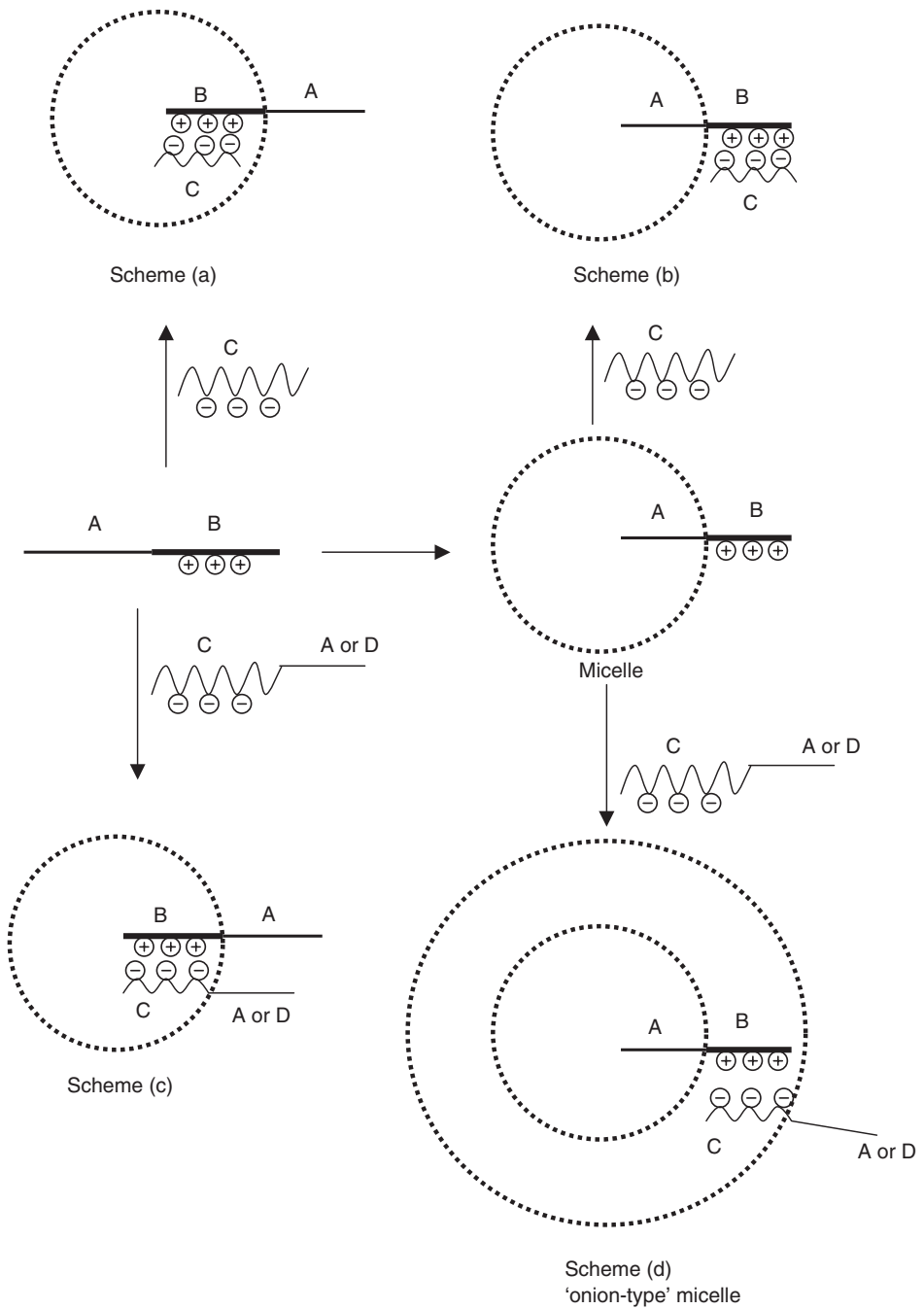
A typical example is that studied by Bakshi *et al.* [259] concerning the interaction of cationic surfactants, for example hexadecyltrimethylammonium bromide (HTBA) with non-ionic PEO-PPO-PEO triblock copolymers. This topic has recently been reviewed by Sastry and Hoffmann [260]. According to these authors both anionic and cationic surfactants, in their micellar or molecular form, interact strongly with the associated and unassociated form of copolymers. The beginning of the interaction is typically displayed as critical aggregation concentration (CAC), which lies always below the CMC of the respective surfactants. The surfactants first bind to the hydrophobic core of the copolymer micelles followed by their interaction with the hydrophilic corona parts. The extend of binding highly depends on the amphiphilic characteristics of the copolymer, the length of the hydrophobic group and the type of head group of the surfactant.

Polyelectrolyte complexes (PEC), also called interpolyelectrolyte complexes (IPEC) are formed by mixing polyelectrolyte chains with oppositely charged complexing agents, either a polyelectrolyte or a low molecular weight surfactant. If this type of complexation involves an ionic block copolymer, the resulting assembly is usually called ‘block ionomer complex’ (BIC) according to Kabanov and co-workers [261, 262], who studied quite extensively these types of complexes. Typical examples of such complexes are those obtained by combination of hydrophilic–hydrophilic block copolymers, like PEO-PMANa with cationic surfactants, or PEO-PEI graft copolymers with anionic surfactants [262, 263]. Neutralization of the charges of the ionic block by surfactant ions leads to the formation and microsegregation of hydrophobic domains. However, agglomeration and macroscopic phase separation are prevented by the presence of the water-soluble non-ionic PEO block. As a result, BIC self-assemble into nanosized particles sterically stabilized in aqueous medium by the PEO blocks.

This concept has been extended to the complex formation between an ionomer block copolymer and either an homopolymer or a copolymer of opposite charges. In addition to these so-called ‘polyion complexes’ (PIC), it should be mentioned that similar complexes can be formed by hydrogen bonds instead of electrostatic interactions as outlined in Section 7.3.10.

Also ‘mixed’ micelles could be obtained by comicellization of PPO-PEO-based copolymers in the presence of a non-ionic  $C_{12}$  (EO)<sub>5</sub> low molecular weight surfactant [264] or by combination of PEO-PPO diblocks and PEO-PPO-PEO triblocks [265]. This topic will not be reviewed further and the following will mainly be focused on supramolecular assemblies formed through specific interactions between a given block copolymer and either a homopolymer or another block copolymers.

The different concepts of comicellization and complex formation are schematically indicated in Figure 7.8 and will be discussed in the following exclusively for aqueous micellar systems.



**Figure 7.8** Schematic structures of micellar PIC. From Ref. [15]. Copyright 2003, with permission from Elsevier.

Let's consider at first a block copolymer A-B where the sequence B can interact specifically, say by electrostatic interaction or hydrogen bonding, with a homopolymer C. In this case a PIC micelle can be formed having a B-C core and stabilizing corona of A (see Figure 7.8, scheme (a)). This possibility was examined by Armes and co-workers [266] for the combination of a PEO-PDEAEMA diblock copolymer with a PMAA homopolymer as a function of pH. At low pH, the micelles are formed by a PEO/PMAA core resulting from the hydrogen bond interaction of PEO and PMAA, the micelles being stabilized by the protonated PDEAEMA block.

At a pH between 3 and 5 no micellization takes place, the different species being molecularly dispersed. In the pH range of 6–8, micellization starts again with a core of the PMAA/PDEAEMA complex and a fringe of PEO, whereas at higher pH, above 8, there is only formation of PDEAEMA core micelles stabilized by PEO in the presence of molecularly dispersed neutralized PMAA.

A similar situation was described by Tenhu and co-workers [267] for a PEO-PMANa diblock copolymer in presence of poly(methacryl oxyethyltrimethylammonium chloride) as cationic homopolymer.

A second possibility is that where the starting copolymer A-B is already under its micellar form. By complexing the B chains in the corona with the polymer C the micellar structure could remain at low ratios of C versus B, however at a stoichiometric amount flocculation could occur (see Figure 7.8, scheme (b)). Examples of this behavior have been examined in our group by Mechergui [268] for PS-PEO micelles where the complex formation occurs by hydrogen bonding between PEO and PMAA in aqueous medium at low pH. A similar system was reported recently by Müller and co-workers [269] where an IPEC was formed between PIB-PMAA<sup>-</sup> Na<sup>+</sup> micelles in aqueous medium and a cationic polyelectrolyte such as poly(*N*-ethyl-4-vinylpyridinium bromide).

The most interesting situation is that where the complex formation occurs between two block copolymers A-B and A-C, respectively C-D, with specific interactions between the blocks B and C (see Figure 7.8, scheme (c)), such PIC, also called block ionomer complexes (BIC) have been studied quite extensively in aqueous medium by Harada and Kataoka [270] and by Kabanov and Alakhov [271] due to their practical interest in controlled delivery systems. Kataoka and co-workers have for instance shown that water-soluble PICs for biomedical applications are formed by combination of PEO-poly(*L*-lysine) and PEO-poly ( $\alpha$ ,  $\beta$ -aspartic acid). These authors have further demonstrated that the PIC micelles prepared under charge-neutralized conditions have an extremely narrow size distribution if matched pairs of copolymers with the same block lengths of polyanions and polycations are combined [272].

A similar system has furthermore been investigated by Gohy *et al.* [215, 245] in the case of complex formation between P2VP-PEO and PEO-PMAA diblock copolymers as well as for combination of a PS-P2VP-PEO triblock with a PAA-PEO comb-block copolymer. The same concept was applied by Tenhu and co-workers [273] involving PEO-PMANa anionic block copolymer and a cationic graft copolymer.

The validity of the concept given in scheme (d) of Figure 7.8 was demonstrated by Weaver *et al.* [274] who obtained CSC micellar structures with a ionically cross-linked shell by polyelectrolyte complexation of a PEO-(quaternized PDMAEMA)-PDEAEMA triblock copolymer micellar system with a PEO – poly(styrene sulfonate) diblock copolymer.

A slightly different approach to the formation of 'onion type' micelles is that described by Prochazka *et al.* [275]. Such structured micelles could be obtained by starting with PtBA-P2VP

precursor micelles in acidic aqueous solution having a PtBA core and a protonated P2VP corona. When this micellar solution is brought to a pH higher than 4.8, the P2VP shell of the micelles collapses and the copolymer precipitates. However, by addition of a water-soluble P2VP-PEO diblock copolymer, its P2VP block coprecipitates with the P2VP corona of the micelles. The complex onion structure is thus stabilized by the PEO blocks. Similar onion type micelles obtained by combination of  $PS_nP2VP_n$  heteroarm star copolymers with a P2VP-PEO diblock copolymer were reported recently by Tsitsilianis *et al.* [276].

## 7.4 Application possibilities of biocompatible copolymer micellar systems

The well-established surface activity of block and graft copolymers, make them of great practical interest as dispersants, emulsifiers, wetting agents, foam stabilizers, flocculants, demulsifiers, viscosity modifiers, etc. . . . , in many industrial and pharmaceutical preparations. These topics are outlined in several review articles [1, 10, 12, 277]. In fact, with respect to classical low molecular weight surfactants, block copolymers have in general a very low CMC and a low diffusion coefficient which is of benefit for micellar systems where the concentration of unimers in equilibrium with the micelles has to be kept to a minimum.

A detailed description of all these application possibilities of block and graft copolymers would exceed the scope of this review. Our aim is rather to highlight some specific aspects where the applications of these copolymers are directly related to their self-organization into micellar systems. This is for instance the case where block and graft copolymers, in form of colloidal dispersions, are of interest for controlled delivery of drugs, diagnostic agents and more recently in gene transfection (gene therapy). These biomedical application possibilities, based on the solubilization of active components in copolymer micelles, will be outlined mainly under the viewpoint of polymer colloids, rather than on biological and medical aspects, such as drug efficiency or toxicity, specific interactions with cells, etc. . . .

Some aspects concerning micellar nanoparticles obtained by complex formation will then shortly be reviewed, as well as some typical features related surface modification of biomedical systems.

### 7.4.1 Solubilization of bioactive components in micellar systems: controlled drug release

In addition to their applications as biomaterials, such as implants, block copolymers and to a minor extend also graft copolymers, have found since the mid-1970s a strong interest in their colloidal form especially as controlled drug-delivery systems, and as carriers of diagnostic agents. These aspects, essentially based on the solubilization capacity of block copolymers micellar systems have been recently reviewed by Riess and co-workers [14, 15], Malmsten [282], Arshady [283] and Torchilin [284]. Major contributions in this area have come from the groups of Kataoka, Yokoyama and Kabanov and their recent overviews illustrate perfectly the current status of the field [285–289].



According to Kabanov and Alakhov [271] three major systems have to be considered for the use of block copolymer micelles in drug delivery:

- (1) Micelle-forming conjugates of drugs and block copolymer, where the drug is covalently linked to one of the sequences of the copolymer.
- (2) Drugs non-covalently incorporated into the block copolymer micelles with formation of so-called 'micellar microcontainers'.
- (3) PEC as those formed with cationic block copolymers.

For these different systems, the main requirements which have to be met, such as biocompatibility, biodegradability, particle size, etc. have been summarized by Kabanov and co-workers [271, 288].

In fact for intravenous applications, it is critical that the drug-loaded micelles are stable and have a low CMC. Otherwise the micelles will dissociate into unimers upon dilution in the bloodstream causing non-targeted drug release and even toxicity.

Various colloidal systems formed with block or graft copolymers, such as liposomes, microspheres, emulsions have been described for oral drug-delivery systems. Block and graft copolymers in their micellar form or as steric stabilizers for colloidal particles are well suited for oral and injectable drug formulations and diagnostic systems if they meet the requirement of biocompatibility and preferably of biodegradability [278, 279].

Due to the large number of amphiphilic copolymers claimed for potential applications as drug release micelles, we shall consider at first the A-B and A-B-A structures, where some of them are specifically functionalized with targeting groups, followed by the more recently developed copolymer structures, for example star, graft A-B-C and polymer complexes.

#### 7.4.1.1 Linear A-B and A-B-A copolymer structures

The early work on micelle-forming block copolymers, with the drug covalently linked to one of the blocks of the copolymer, was reported by Ringsdorf and co-workers [280]. Starting with a PEO-*b*-poly(L-lysine) diblock copolymer, these authors fixed covalently the drug 'cyclophosphamide' on the L-lysine block leading to micelles with a hydrophobic core of modified L-lysine and a hydrophilic PEO fringe. A similar approach was later described by Yokoyama *et al.* [281] using PEO-poly(aspartic acid) block copolymer modified with doxorubicin. Even more elaborate structures were developed for this type of copolymers in order to increase the activity of drug. If this approach is still of interest for water-soluble drugs, the main limitation for the controlled drug release of hydrophobic drug molecules by this strategy is that specific block copolymers, with suitable functional groups, spacers and cleavable bonds, have to be designed for a given kind of drug.

'Micellar microcontainers', where the hydrophobic drug is solubilized, for example non-covalently fixed, in the hydrophobic core of copolymers micelles, became therefore the preferred strategy in the last years, especially with the possibility to provide these micellar systems with targeting function and stimuli sensitive properties.

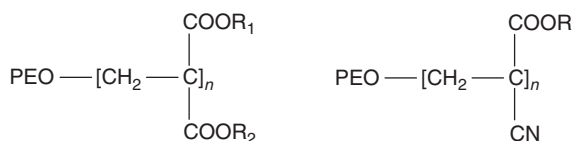
The large variety of amphiphilic block copolymers developed for these applications are those containing a poly(aminoacid), a poly(ester) or a poly(anhydride) hydrolytic and/or enzymatic degradable block, with their hydrophilic moiety mostly consisting of ethylene oxide oligomers or polymers: PEG or PEO. This type of water-soluble polymers, approved by FDA for biomedical applications, have numerous other advantages, such as rapid clearance

from the body, lack of immunogenicity, etc. [290]. PLA-PEO, PLGA-PEO and PCL-PEO are typical examples of polyester-based block copolymers that have extensively been studied over the last years in view of their biomedical applications, with the recent examples being those of Geng and Discher [291] and Shuai *et al.* [292].

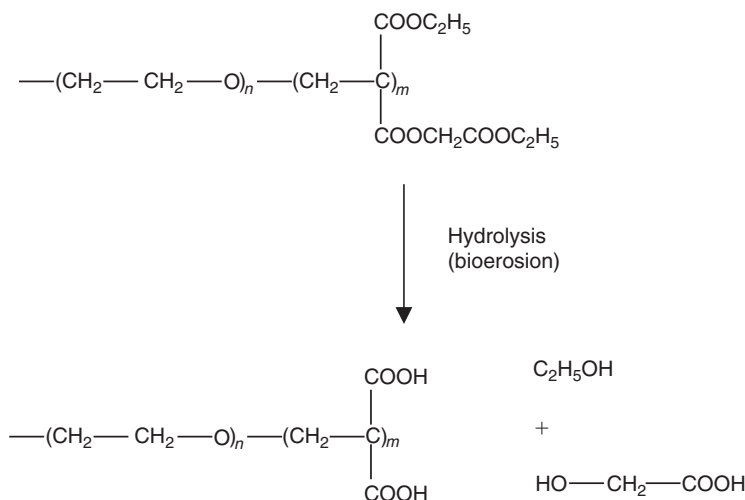
PEO-PPO di-, tri- or multiblock were certainly one of the first types of amphiphilic block copolymers described in the literature. Their properties and biomedical application possibilities having extensively been described by Kabanov *et al.* [271, 288], we will not further insist on this type of copolymers.

Other examples of recently developed block copolymers based on PEO are those having poly(styrene oxide) [293], poly(allylglycidyl ether) as a cross-linkable block [294] or poly(methylidene malonates) [171, 295] as hydrophobic micellar core-forming blocks.

This last type of copolymers developed in our group for biomedical application, are somehow analogous to poly(cyanoacrylates) copolymers studied by Couvreur [296] as shown in the following scheme:

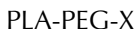


Of special interest are the malonate sequences with  $R_1 = \text{C}_2\text{H}_5$  and  $R_2 = \text{CH}_2\text{—COO—C}_2\text{H}_5$  abbreviated PMM 212 for which it was shown by Lescure *et al.* [297] that the degradation occurs 'in vivo' by elimination of ethanol and glycolic acid as indicated in the following scheme:



After bioerosion of the poly(malonate) sequence the block copolymer will be formed by two water-soluble sequences which in contrast to the starting PEO-PMM 212 copolymer has no longer a tendency to form micelles. Solubilization of drugs in this type of bioerodible micelles appeared to be very promising as drug carrier and controlled delivery systems because their toxicity is quite reduced with respect to poly(cyanoacrylates).

In continuation of their pioneering work on polymeric micelles as drug release systems Kataoka and co-worker [285, 286, 298] have introduced the concept of active targeting for micellar systems. This means that chemical modification of the terminal groups of the PEO block provides the possibility of incorporating 'vector molecules' in the hydrophilic corona for the site-specific targeting of the resulting micelles. A typical example described by these authors is that of heterotelechelic PEG-poly(lactide) block copolymers of the following structure:



where X can be an aldehyde, amino or a saccharide moiety. Other examples were reported by Lim *et al.* [299] and by Studer *et al.* [300] who succeeded in the preparation of PMM 212-PEO diblock copolymers bearing a mannose end-function as targeting group.

Various other combinations of hydrophobic-hydrophilic blocks are of interest as 'micellar microcontainers' in drug-delivery applications, such poly(DL lactide)-poly(*N*-vinyl-2 pyrrolidone) [301], poly(lactide)-depsipeptide [302], poly(malic acid)-poly(malic ester) [303], dendrimer unimolecular micelles [304], etc.

Promising developments are further expected from stimuli sensitive, mainly pH and thermoresponsive systems that change their volume and shape according to external physicochemical factors. Typical examples of such block copolymer micelles mainly based on PNIPAM were described by different authors [176, 177, 305, 306].

#### 7.4.1.2 Complex molecular architectures and complexes

Several amphiphilic star-block copolymers comprising biodegradable hydrophobic blocks, such as PCL, PLGA or PBLG and biocompatible hydrophilic sequences were synthesized by Li and Kissel [307] and by Jeong *et al.* [308] for biomedical applications. Star structures have the advantage that at a given molecular weight star blocks lead to smaller particles than the corresponding diblocks.

A typical example of graft copolymers is that recently published by Winnik and co-workers [309]. These authors have studied the solubilization of cyclosporine A, as a model drug, in micellar systems based on hydroxypropylcellulose-*g*-polyoxyethylene alkyl ether. They could demonstrate that the drug loading in the micelles, with diameters ranging from 78 to 90 nm, increases with the number of grafted chains.

A-B-C structures are another possibility to develop new properties of polymeric nanocarriers for drug release. This approach was examined for instance by Kim *et al.* [310], with PEO-PPO-PCL triblock copolymers, by Deng *et al.* [108] with PEG-*b*-PLLA-*b*-PLGA and by Gadzinowski *et al.* [311] with PEO-*b*-poly(glycidol)-*b*-PLLA.

Of special interest are the biodegradable cationic block copolymers, such as PEG-PEI-PBLG hyperbranched triblock copolymers and the linear A-B-C type developed by Tian *et al.* [312] and by Kataoka and co-workers [313], respectively. These copolymers have potential medical applications in drug and non-viral gene delivery, due to their ability to form PEC.

In fact it has been shown, that copolymer with a cationic block, such as PEI [63, 312, 314–316], but also polylysine [313, 317–319] or PDMAEMA [320–322], in combination with a water-soluble PEO block can be used for the complexation of anionic species like oligonucleotides, plasmid DNA or other protein drugs, in order to provide new pharmaceutical forms for gene therapy [323].

Mention should finally be made that loading of block copolymer micelles by complexation with contrast agents, for example with colloidal metals or components with heavy elements, such as bromine or iodine, opens interesting application possibilities for certain therapies and in medical diagnostic imaging [324].

These different examples illustrate the major interest of block copolymers, and to some extent also of graft copolymers, in form of 'micellar microcontainers'. In fact, as pointed out by Kabanov and co-workers [271, 288], one can adjust the chemical nature of blocks as well as the molecular characteristics (molecular weight, composition, presence of functional groups for active targeting) within an homologous block copolymer series to optimize the performance of the drug for a given drug-delivery situation.

The advantages of block copolymers are furthermore that:

- The micelle dimension are easily adjustable in the range of 10–100 nm, which is a major requirement for injectable formulations.
- The CMC, the diffusion coefficient of the micelles and that of the corresponding unimers are generally very low, as compared to low molecular weight surfactants; these parameters are important for drug-delivery applications since they determine the stability of the micelles during dilution occurring in biological fluids.
- End-group functionalization increases the targeting efficiency.
- Frozen- or cross-linked micelles allow a longer retention of the loaded drug and a higher drug concentration at the target site [278].
- The partition coefficient of the drug, for example its distribution between the micelles and the aqueous phase, as well as the total amount of solubilized drug can be adjusted as a function of the micellar characteristics as clearly demonstrated by Nagarajan and Ganesh [142] and by Kozlov *et al.* [325].

### 7.4.2 *Miscellaneous biomedical applications*

A great number of experimental and theoretical studies have been published concerning the surface modification of biomedical devices by block copolymers in order to promote-specific characteristics, for example wetting, improved biocompatibility, etc. For the surface modification by block and graft copolymers, it is important to determine not only the conformation and the surfaces density of the adsorbed chains in form of a brush, but also the kinetics of this phenomenon which in fact will depend on the unimer-micelle equilibrium.

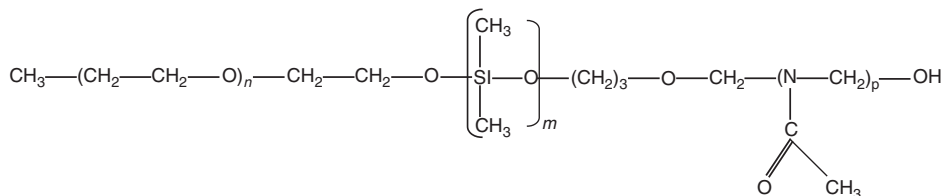
The theories and the experimental aspects concerning self-assembly of block copolymers at surfaces have been reviewed by Tirrell [326] and by Hamley [11]. Hamley has given in addition an overview on the various morphologies of thin block copolymer films confined on a surface.

For biomedical applications, which will only be considered in this review, it could be mentioned that Kataoka and co-workers [327] prepared non-fouling surfaces by coating them with core-polymerized PEG-PLA block copolymer micelles having an aldehyde-ended PEG shell.

Hydrophilization of surfaces with PS-PEO graft copolymers and the chain conformation in the adsorbed layer has been studied in detail by Yokoyama *et al.* [328].

The problem of controlled drug release from surface coated stents with PMMA-PIB-PMMA and PHEMA-PIB-PHEMA triblock copolymers was recently approached by Cho *et al.* [329]. Drug eluting stents are in fact one of the most recent advances in the treatment of cardiovascular disease.

Vesicle formation with block copolymers, for example with PB-poly(L-glutamate), is well documented in the literature [330]. So-called stealth liposomes could be prepared by Nuyken *et al.* [331] by combining phospholipids with poly(oxazoline) based A-B-C triblock copolymers. In this context, Meier and co-workers [332] succeeded in preparing asymmetric membrane structures, by insertion of membrane proteins into amphiphilic A-B-C triblock copolymers with two water-soluble blocks A and C, such as PEO-PDMS-poly(2-methyloxazoline) of the following structure:



## 7.5 Conclusions

From this overview and from Hadjichristidis *et al.* [13] recently published book, it is evident that amphiphilic block and graft copolymers are an interesting class of polymeric surfactants. They are unique in that they self-assemble into nanoparticles with well-defined sizes and morphologies.

Considerable progress has been made in the synthesis of 'tailor-made' block copolymers, and to some extent also to the corresponding graft copolymers, by living ionic polymerization, controlled free-radical polymerization and quite recently by non-covalent coupling techniques. Numerous examples of linear 'water-soluble' A-B and A-B-A structures were described in addition to the possibility of functionalization of these copolymers with specific groups, such as reactive double bonds, ionic groups, fluorescence labels, either at the chain ends and/or at the junction of the blocks.

A wide range of more sophisticated structures, such as linear or star-shaped A-B or A-B-C, H-shaped, brush structures, etc., comprising water-soluble blocks have been prepared. The systematic study of their micellization behavior has recently just been started.

The present overview demonstrates that there is almost no limits in the design of original structures and new types of amphiphilic copolymers, including those of hydrophilic-hydrophilic type, that are of promising interest as shown for instance by Cölfen [213].

One of the remaining challenges for the synthesis chemist would be to provide 'pure' and well-characterized copolymers, especially of very low polydispersity (in structure, molecular weight and composition) and devoid of impurities (initiator residues, homopolymers, etc.), which could have a strong influence on the micellization behavior as well as on the final properties.

In this respect, enzymatic catalysis could be an interesting alternative for the production of biocompatible copolymers, as recently demonstrated by a dutch group for the synthesis of PCL-PS diblock copolymers [333].

Block and graft copolymers as amphiphiles mainly differ from conventional surfactants by the length of hydrophobic and hydrophilic moieties. As a direct consequence the self-assembly of polymeric surfactants, via a so-called closed association process, is characterized by low CMC values.

Stable core-shell micelles, with particle sizes up to 80–100 nm are easily obtained and their morphology can be tailored as a function of the copolymer structure. Thus A-B-C structures lead to CSC micelles, whereas unimolecular micelles may be formed with starblock and certain graft copolymers.

A considerable set of data is available concerning the micellization, mainly of linear A-B, A-B-A or B-A-B copolymers in aqueous medium. However, even for a given type of copolymer, great attention has to be paid to the preparation step of the micellar system. In fact, one has to be aware that the simple dissolution of the copolymer in water, as the selective solvent, could lead to non-equilibrium situations the so-called 'frozen micelles' and to fractionation during the micellization process, which is mostly inherent to the polydispersity of the starting sample. This phenomena of forming 'frozen micelles', which otherwise can be of practical interest, raises however fundamental questions related to the CMC determinations and to the micellization kinetics. These problems, as well as those coming up by complex formation between the different blocks of a given copolymer, that has been observed for double-hydrophilic copolymers, for example PEO-PMAA, are still under debate and would need further investigations.

Concerning the application possibilities, block and graft copolymers micelles and their assemblies as PIC are of great practical importance. Of special interest, as outlined in this review, are amphiphilic copolymers with biocompatible and biodegradable sequences, that have obtained growing attention as controlled drug-delivery systems and as potential carriers in gene therapy.

## Acknowledgments

The author would like to express his gratitude to his former Ph.D. students and post-docs mentioned in this review for their contributions, as well as to Prof. M. Popa, Ms. J. Paytuyi and Dr. K. Hariri for their technical assistance.

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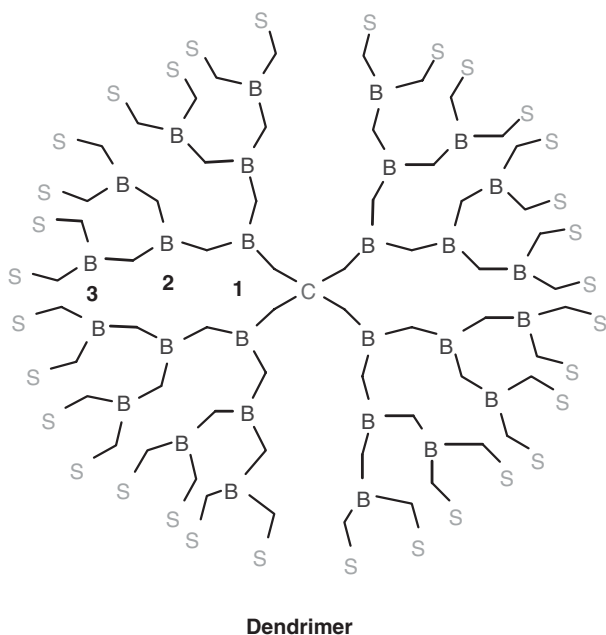
## Chapter 8

# Applications of Water-Soluble Dendrimers

*Philip Woodward, Steven Rannard and  
Wayne Hayes*

### 8.1 Introduction

The term 'dendrimer' is derived from the greek '*dendra*' = *tree* and '*meros*' = *part* and describes graphically the structure of this new class of macromolecules which have highly branched, three-dimensional features that resemble the architecture of a tree [1]. A typical dendrimer (Figure 8.1) consists of three main structural components: a multifunctional central core (C), branched units (B) and surface groups (S). The branched units are organised in layers referred to as 'generations' (described typically using the shorthand notation '[G-*n*]', where G is the generation and *n* is an integer value), and represent the repeating monomer unit of these macromolecules. Dendrimers are characterised by an ideally branched structure and the presence of a high number of functional groups, which can have a significant effect



**Figure 8.1** Generic architecture of a third generation ([G-3])dendrimer [1].



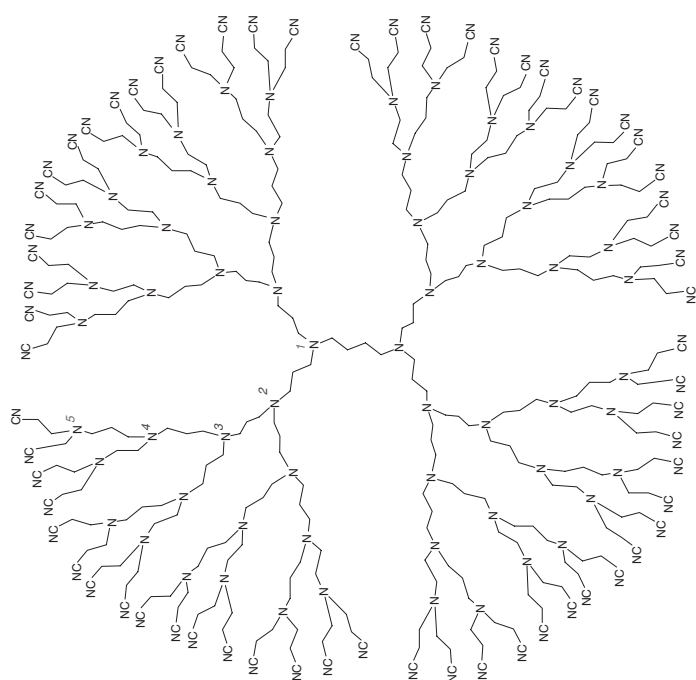
upon the physical properties both in the solid state and in solution [2, 3]. Furthermore, the macromolecular dimensions can be controlled since the synthesis involves a repetitive sequence of steps. Dendrimers are synthesised from monomers of the  $AB_x$  type (where  $x \geq 2$ ) through a step-growth polymerisation process.

There are two general synthetic approaches used to generate dendrimers: (i) *divergent* and (ii) *convergent*. Both synthetic strategies possess relative advantages and disadvantages – the appropriate choice of synthetic route used is influenced strongly by the monomer type employed and the target polymer structure. Although Flory first reported the potential role of highly branched structures in macromolecular systems in 1952 [4], the first synthetic examples of branched macromolecules obtained by the divergent approach were only described in the late 1970s by Vögtle and co-workers, who referred to the synthesis as a ‘cascade approach’ [5]. In 1984, Tomalia and co-workers published the synthesis and full characterisation of a novel class of poly(amidoamine) (PAMAM) macromolecules (Figure 8.2a), and referred to these hyperbranched polymers as ‘dendrimers’ [1, 6]. This divergent synthesis commenced with a Michael addition of a molecule of ammonia (the dendritic core) to three molecules of methyl acrylate, followed by exhaustive amidation of the esters by an excess of ethylenediamine, generating a macromolecule with six primary amine groups. The exhaustive Michael addition–amidation reaction sequence was then repeated in an iterative fashion to achieve an almost monodisperse dendritic structure with a molecular weight of over 25,000 Da – dendrimers of this type are now available commercially under the trade name ‘Starburst Dendrimers’<sup>TM</sup>. Another class of dendrimer that have been ‘grown’ in a divergent fashion and have proved popular in studies of applications are the polypropyleneimine (PPI) dendrimers (Figure 8.2b) [7]. In a route related closely to the synthetic approach described by Vögtle and co-workers, the PPI polyamine dendrimers are grown via a repetitive sequence of Michael addition–reduction reactions using acrylonitrile as the monomer.

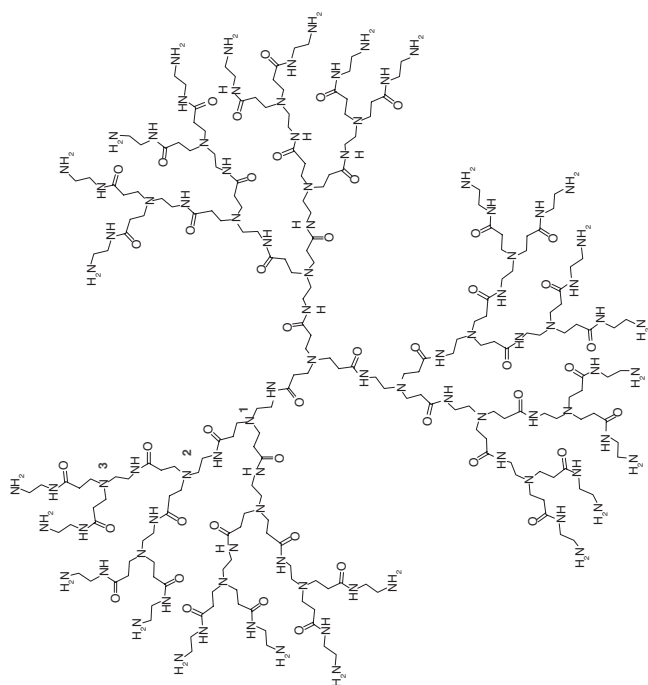
In 1989, Fréchet and co-workers first reported the convergent growth approach [8, 9]. In contrast to the divergent growth approach, dendrimer construction is initiated at what will eventually become the outer surface shell of the ideally branched macromolecule and proceeds inward, by a stepwise addition of branching monomers, followed by the final attachment of each branched dendritic sub-unit (or ‘dendron’) to a poly-functional core. This synthesis generated a poly(aromatic ether) dendrimer and a repetitive sequence of Williamson ether coupling and bromination reactions were employed as shown in Scheme 8.1.

These three dendrimer systems have proved to be excellent structural frameworks from which to explore the potential applications of dendrimers and thus this chapter will feature numerous examples of their use. The remit of this review is not, however, to provide a detailed coverage of the synthetic approaches used to generate the diverse range of dendrimers described herein. Several excellent reviews have been written on this subject and the reader is directed to these articles [10–13].

It has been observed that when a dendrimer reaches a specific generation (a variable factor according to the dendritic structure but in general equal to or greater than generation four) a significant conformational change occurs and the structure assumes a densely packed globular shape. This change in conformation correlates with a decrease in chain entanglements and molecular aspect ratio [14], therefore conferring different solution and bulk properties to dendrimers in comparison to their linear analogues [2, 14]. An important area where linear and dendritic polymers exhibit diverse characteristics is their viscosity

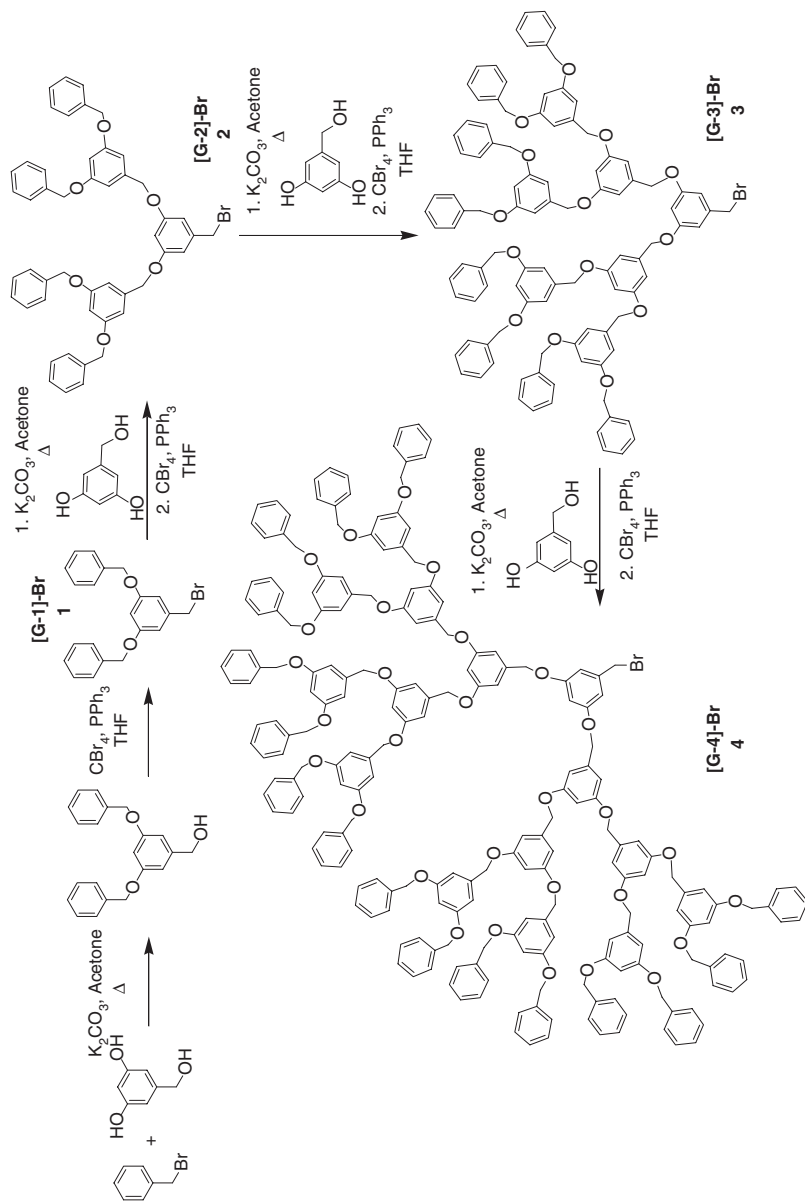


(b)



(a)

**Figure 8.2** (a) Third generation PAMAM dendrimer [1, 6] and (b) Fifth generation PPi dendrimer [7].



**Scheme 8.1** The convergent route towards the synthesis of poly(aryl ether) dendrimers described by Fréchet and co-workers [8, 9]

behaviour. It is well known that the intrinsic viscosity of a linear polymer increases with the increase of molecular weight ( $M_w$ ) according to the Mark–Houwink–Sakurada relationship [15]. However, dendrimers exhibit a linear relationship at lower generation numbers and a maximum that corresponds to the change in shape, followed by a smooth decrease in intrinsic viscosity at higher molecular weight [1, 12, 16].

Another important characteristic of dendritic molecules is their high solubility in a large number of solvents, thereby potentially offering improved processability characteristics and rapid dissolution [17].

These distinguishing features of dendritic macromolecules render these novel materials a reliable alternative to traditional polymers in a wide range of potential applications. The primary focus of this chapter is to cover the range of these potential uses of water-soluble dendrimers – it does not provide comprehensive coverage of these applications but has targeted a number of notable examples of the utilisation of water-soluble hyperbranched macromolecules.

## 8.2 Medical applications of dendrimers

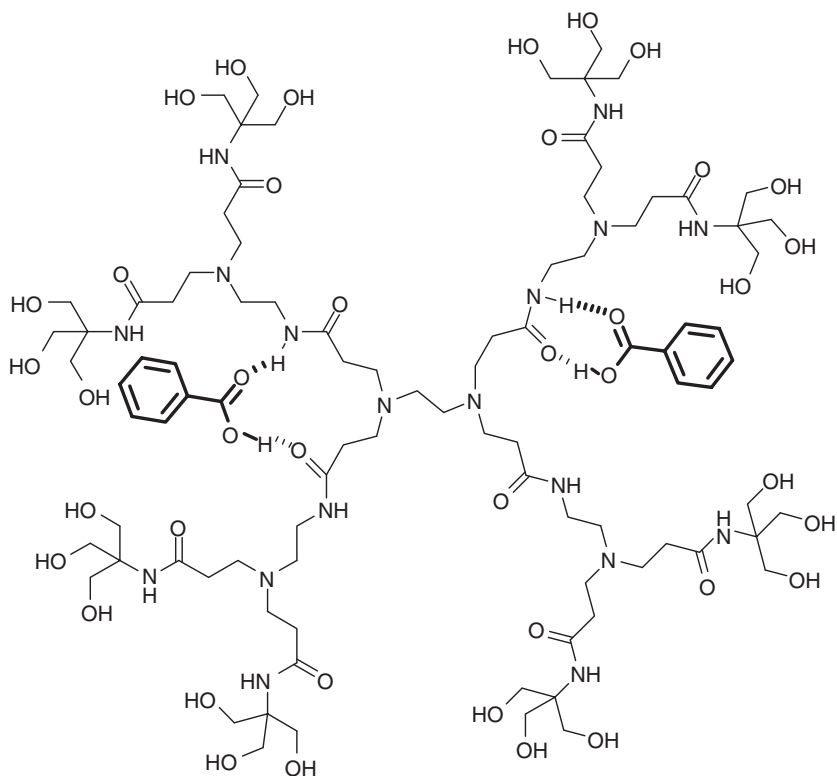
One of the largest research areas in which applications of dendrimers are being investigated is in the medicinal field [18]. The potential of dendrimers in medicine encompasses a wide range of functions ranging from drug delivery and therapeutic agents to contrast agents used in X-ray and magnetic resonance imaging (MRI).

### 8.2.1 Dendritic drug delivery systems

Dendrimers have been targeted in medical applications such as drug delivery as a consequence of their advantageous solubility characteristics, coupled to their multifunctional architecture, which enables drugs to be bound on or within the dendrimer, either via covalent or non-covalent means.

The amphiphilic nature of specific dendrimer types allows them to act in solution in a micellar manner with the advantage of increased stability with respect to dynamic, non-covalent surfactant-based micelles. A dendrimer featuring a hydrophobic core that is functionalised with hydrophilic end groups can solubilise an apolar drug that would otherwise prove insoluble in the aqueous *in vivo* environment. Several notable examples of this strategy, to solubilise poorly soluble drugs by their inclusion in dendrimer micelle complexes, have been reported. For example, PPI dendrimers have been investigated as pH sensitive controlled release systems [19]. Protonation of the tertiary amine residues within the dendritic architecture was found to effect release of an apolar aromatic model compound (pyrene) in acidic media thereby demonstrating the suitability of this system as a potential ‘smart’ drug release agent.

An important class of water-soluble dendrimers – the PAMAM dendrimers – have also been investigated as drug delivery systems. Twyman and co-workers have demonstrated that hydroxyl terminated water-soluble PAMAM dendrimer systems were capable of encapsulating small acidic hydrophobic molecules such as benzoic acid (Figure 8.3). The encapsulation capabilities of the PAMAM materials was first confined to benzoic acids and



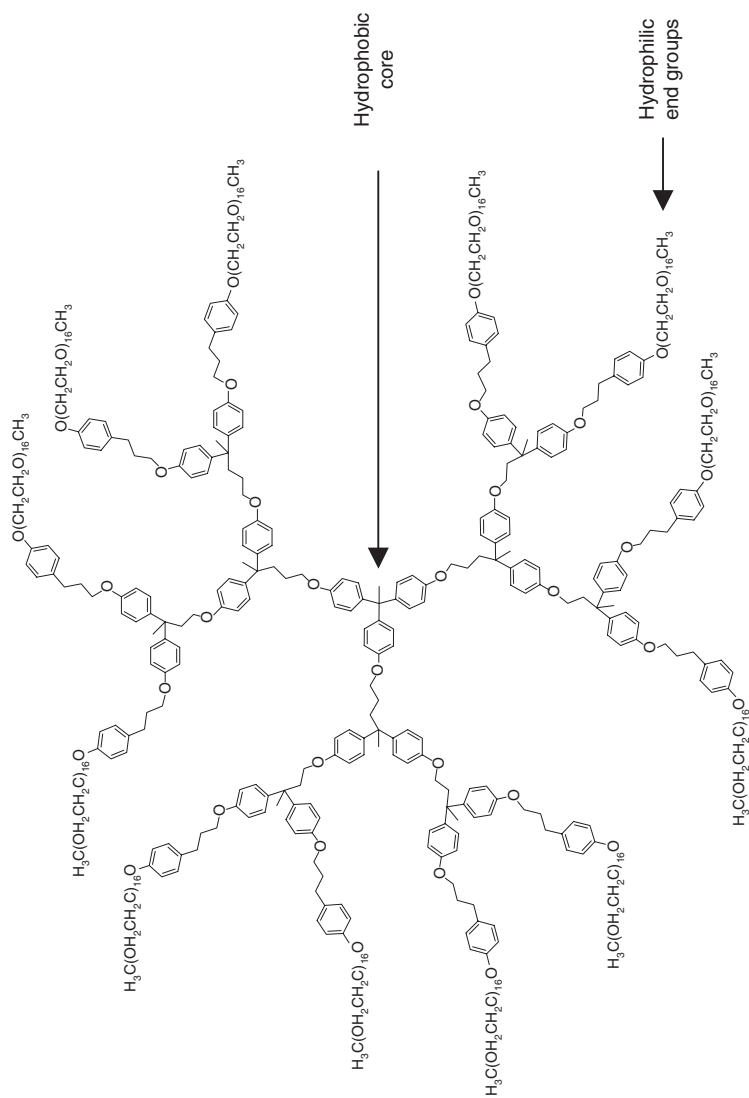
**Figure 8.3** The complexation of a benzoic acid guest in a hydroxyl terminated PAMAM dendrimer that was reported by Twyman and co-workers [20].

phenols [20] as non-covalently bound guests but was later extended successfully to the inclusion, and subsequent release, of a range of anti-bacterial agents [21].

PAMAM dendrimers have also been used as ligands for platinate chemotherapy agents with the platinate moieties acting as cross-linkers between dendrimer molecules [22]. Highly water-soluble dendritic complexes were thus formed which released platinum slowly *in vitro*. *In vivo* studies revealed that the platinate–dendrimer complexes compared favourably with *cis*-platin, especially exhibiting activity towards tumours against which *cis*-platin was ineffective, and increased the accumulation of platinate in tumours and reduced the toxicity thus allowing for higher doses to be applied.

In related studies, Fréchet and co-workers pioneered the use of a dendrimer system that was based upon benzyl and phenyl ether repeat units (Figure 8.4). Using this system, a hydrophobic core was used to effectively ‘dissolve’ pyrene and the model drug indomethacin, whilst functionalisation of the peripheral dendrimer end groups with poly(ethylene glycol) units conferred aqueous solubility onto the resultant dendrimer drug complex [23]. Drug loading values up to 11 wt.% were achieved in this dendrimer system and preliminary *in vitro* release tests showed that a sustained drug release profile was achieved.

The solubility characteristics of poly(ethylene glycol) systems in water has led to the employment of this polymer in alternative drug delivery systems. For example, Schlüter

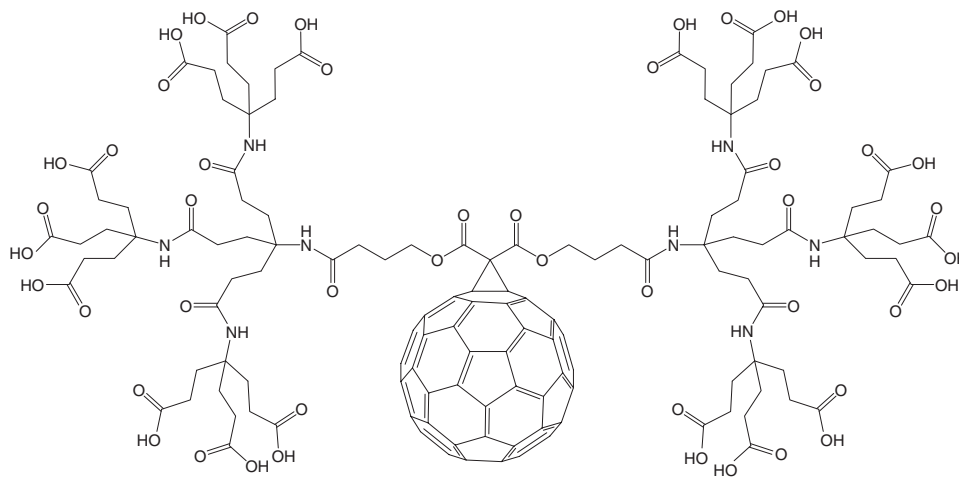


**Figure 8.4** The PEG terminated poly(aryl ether) dendritic drug delivery system reported by Fréchet and co-workers [23].

and co-workers have synthesised a range of dendrons that possess multiple ethylene glycol moieties as solubilisers for the modification of commercially available non-water-soluble dendrimers [24]. Park and co-workers have also employed poly(ethylene glycol) dendrimers for the hydrotropic solubilisation of the drug Paclitaxel [25, 26]. These hydrophilic dendrimers did not act as micelles and were not bound covalently to the drug – solubilisation was achieved as a result of the dendritic architecture surrounding aromatic and methyne groups of the drug, thereby offering an alternative approach to solubilising poorly soluble drugs. Paclitaxel was thereby rendered bioavailable by combination with a highly water-soluble dendrimer and as a consequence the solubility of the hydrophobic drug was increased approximately 10,000-fold. Drug release was achieved via *N,N*-diethylnicotinamide as the release medium and the release rate was found to be dependent upon the generation of dendrimer used.

In addition to micelle based and hydrotropic solubilisation of drugs, systems where drugs are bonded covalently to the solubilising dendrimer systems, thus effectively forming pro-drugs, are also now becoming commonplace. Fréchet and co-workers employed poly(ethylene glycol) terminated dendrimers that were coated with covalently bound cholesterol and two amino acids as model drug compounds [27]. Alternative examples of dendrimer prodrugs include the anti-viral agent Acyclovir with a thiophosphate dendrimer [28], the novel anti-depressant Venlafaxine with anionic PAMAM dendrimers and a poly(ethylene glycol) system containing semi-interpenetrating networks [29], the anti-inflammatory drug 5-aminosalicylic acid with PAMAM dendrimers [30] and the highly potent anti-cancer drug Doxorubicin with polyester-based dendrimers [31].

An interesting therapeutic agent has been reported that features the attachment of C60 fullerene units to alkylpolyamide dendrimers to affect water-solubility upon the polycyclic fullerene group. Fullerenes exhibit extraordinary radical scavenger properties and are thus ideal candidates for therapeutic agents against neurodegenerative diseases. For example, the highly water-soluble dendro(60)fullerene was synthesised by Hirsch and co-workers [32] (Figure 8.5) and has been reported [33] as a treatment for HIV infections.



**Figure 8.5** The anti-neurodegenerative dendro(60)fullerene described by Hirsch and co-workers [32, 33].

Poly(amidoamine) dendrimers have also been used to derivatise fullerenes with similar applications in mind [34].

Baker and co-workers have carried out a comparative study of covalently and non-covalently bound PAMAM dendrimeric drug complexes [35]. This study concluded that in the case of the fifth generation PAMAM dendrimer and the drug methotrexate, covalently bound dendrimer drug complexes proved to be more effective at specifically targeted drug delivery whereas non-covalently bound dendrimer drug complexes released the drug far too readily.

Another medical application that could take advantage of the novel properties of dendrimers is bioadhesives and phase change polymer drugs. In particular, the application of dendrimers in ocular drug delivery is of significant interest. Drugs administered to the eyes can be problematic as a result of the fluid environment and associated loss of drug solution that normally occurs. Potential solutions to this problem are drugs that adhere to the surface of the eye or undergo a rapid increase in viscosity as a result of a change in temperature or pH. Robinson and Mlynek have proposed that dendrimers could be an ideal drug delivery system in either of these two application mechanisms [36].

From this short review of the use of water-soluble dendrimers in drug delivery, it is clear that there is great promise for these hyperbranched polymers in this field. Further research effort in this area on both covalent and non-covalently bound drugs will continue to advance the understanding of the key criteria that need to be satisfied in order to make successful dendrimer-drug candidates. A suitable dendrimer should combine high aqueous solubility whilst retaining sufficient stability, and even substrate selectivity, in a manner that will make it suitable to be administered to humans or animals. To date, dendrimer-based drugs have not reached the market as therapeutic agents, however, several systems are performing promisingly in preclinical and clinical trials. With the significant research activity that is underway in this area worldwide, both in academic and commercial laboratories, it is plausible to suggest that dendrimer-based drugs will be realised in the near future.

### **8.2.2 Dendrimer mediated gene transfection**

Modulation of the expression of genes can be a highly effective way of combating viral, oncological and haematological diseases. A variety of dendrimer systems have been utilised to demonstrate the efficacy and inherent potential of these hyperbranched polymers for this purpose. The phosphorus containing dendrimers, developed by Majoral and co-workers, have been shown to be effective as gene transfection agents to deliver genetic information in the form of DNA or RNA for gene therapy [37–39]. These systems were used to demonstrate the principle by transfecting luciferase plasmid pCMV-luc into the eukaryotic cells NIH 3T3 murine fibroblasts. A functional test was also carried out by transfecting a DNA plasmid carrying the functional gene of enhanced green fluorescent protein into HeLa cells. Spectrophotometric measurements were then used to demonstrate the successful uptake and expression of the gene.

A PAMAM-PEG-PAMAM dendritic triblock copolymer has also been shown to be an efficient gene delivery agent [40]. Plasmid DNA was found to assemble with the copolymer forming compact nanosized particles with a narrow size distribution. The resulting complex exhibited high solubility when compared to PAMAM dendrimers, low-cytotoxicity



and high-transfection efficiency. Park and co-workers have also demonstrated the efficiency of a PEG-poly(L-lysine) block copolymer system in assembling with plasmid DNA, however, the results of transfection tests involving these copolymers have not yet been reported [41]. Finally, Szoka and co-workers have demonstrated that PAMAM cascade polymers are also highly efficient transfection agents [42].

### 8.2.3 Dendritic medical imaging systems

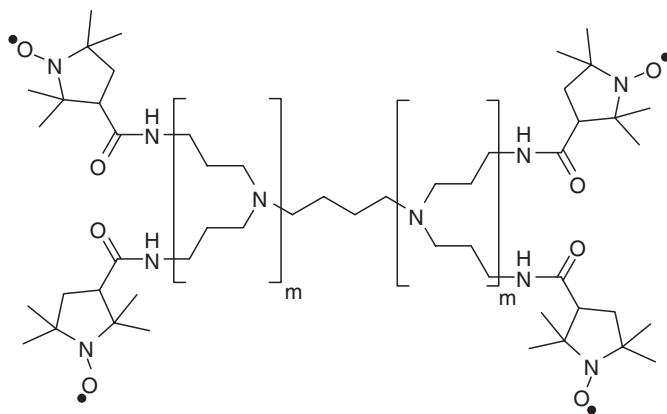
Medical imaging is now a well-established field that encompasses techniques ranging from X-ray scanning to newer methods, such as MRI. Improvements in this field have been achieved by the utilisation of pigments, dyes and contrast agents. The need for aqueous soluble pigments, dyes or contrast agents in these techniques makes dendrimers a natural choice for use in their formulation.

An MRI system images the body in a manner similar to that employed by a conventional nuclear magnetic resonance (NMR) spectrometer when analysing organic compounds. The variety of tissues and organs in the body feature different water contents and thus exhibit differential responses and can be distinguished from one another using MRI. However, water content differences between tissues and, in particular, between normal tissue and tumours, are not significant and visualising tumours has thus proved difficult. Consequently, contrast agents that are incorporated selectively into tumours, and thus serve to increase visibility of these uncontrolled growths, are desirable.

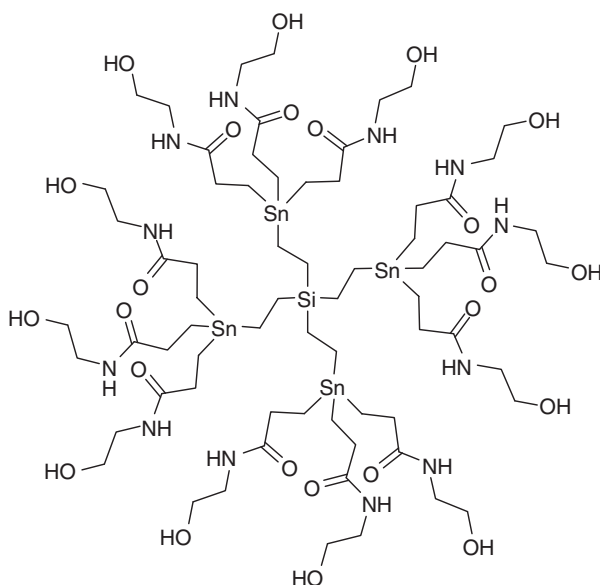
Gadolinium increases the relaxation rates of protons thereby increasing the signal observed in NMR or MRI analyses. There are numerous gadolinium-based contrast agents that are commercially available. The unique properties of dendrimers have proved particularly advantageous in conjunction with gadolinium in this application. Modification of the periphery of PAMAM dendrimers with gadolinium containing macrocycles by Margerum and co-workers generated very effective contrast agents with extended blood elimination half-lives and increased relaxation rate of aqueous protons [43]. A similar approach placed a single central gadolinium complex at the centre of a polyether dendrimer with numerous solubilising terminal hydroxyl moieties [44]. A large alteration of the relaxation rate of aqueous protons was also observed and implied that this dendrimer-gadolinium complex was a viable route to biologically suitable MRI contrast agents. Kawa and co-workers have synthesised gadolinium-cored poly(ether amide) dendrimers for MRI contrast agents [45]. Enhanced proton relaxation times were observed in conjunction with a high stability of the central gadolinium complex as a result of the dendritic building blocks used, leading to potential benefits of decreased toxicity of these reagents *in vivo*.

An interesting study of potential dendrimer-based MRI contrast agents, that was not based upon the proton relaxation enhancing properties of gadolinium, was carried out by Meijer and co-workers [46]. Proton relaxation studies were carried out on nitroxyl bearing PPI dendrimers (Figure 8.6) and revealed that as a result of an increased rotational correlation time, the dendrimer architecture conferred an enhanced proton relaxation on the nitroxyl moieties when compared to mononitroxyl species.

Analysis of the human body using X-ray irradiation is a well-established technique when compared to MRI scanning and has thus benefited from extensive research into contrast agents (such as tin complexes) in order to increase the sensitivity of this method.



**Figure 8.6** The nitroxyl terminated dendrimer proton relaxation enhancement agent for potential use in MRI [46].



**Figure 8.7** A water-soluble functionalised tin-based metallodendrimer developed for applications in X-ray scanning [47].

Schumann and co-workers have reported the construction of a hydrophobic tin-based metallodendrimer system that features hydrophilic terminal groups (Figure 8.7), in order to confer aqueous solubility on the densely loaded metalcore [47]. It was hoped that a high loading of the metal would enhance the contrast capabilities of this metallodendrimer system. Favourably, the water-soluble tin-based dendrimers exhibited low toxicities in mice ( $LD_{50}$  values of 3 mmol Sn/kg body weight) and these materials are thus potential

candidates for use as X-ray contrast agents. However, further development work is required in order for these metallodendrimer systems to be commercialised.

Another notable example of the use of dendrimers for medical imaging are the PAMAM and PAMAM/poly(ethylene glycol) based systems described by Vinogradov and co-workers [48]. The palladium complexes of tetrabenzoporphyrin, at the core of water-soluble dendrimers, acted as strong infrared phosphors that are suitable for tissue oxygen imaging via phosphorescence quenching. The complexes synthesised exhibited excellent optical properties, making them suitable for *in vivo* oxygen imaging, but these materials suffered from core–core aggregation, a problem which needs to be addressed before these palladium–porphyrin–dendrimer complexes can be used in clinical trials.

### 8.2.4 Other medical applications of dendrimers

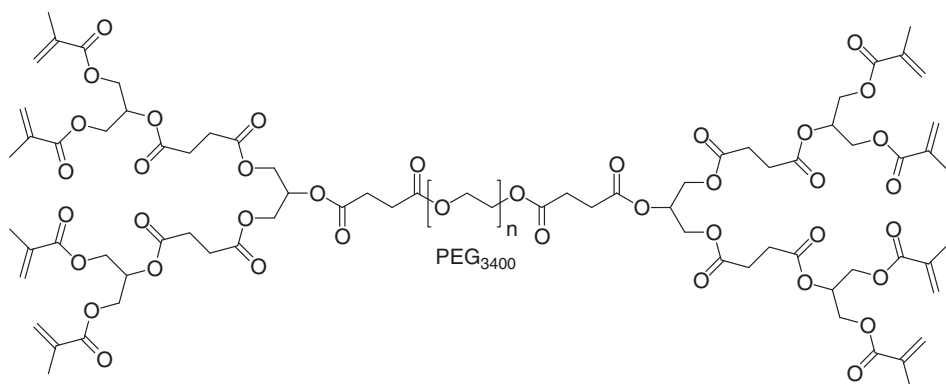
In addition to well-established concepts of the use of dendrimers in drug and gene delivery and medical imaging, there are many other potential medical applications that have been envisaged for dendrimers that take advantage of their unusual physical and chemical properties. Notable examples include PAMAM-based glucosamine dendrimer conjugates for the prevention of scar tissue formation [49], diaminobutane dendrimers as bioartificial livers [50], poly(aryl ethers) as biomimetic active site analogues [51], PAMAM dendrimers coupled to anti-bodies for immunoassays [52] and a polyphenylene dendrimer detergent complex as a fluorescent probe for bioassays [53].

Poly(ethylene glycol) and poly(glycerol succinic acid) triblock dendrimers were utilised as potential photo-crosslinkable cartilage repair media by Grinstaff and co-workers [54]. A water-soluble poly(ethylene glycol) mid-section was functionalised at each end with methacrylate terminated poly(glycerol succinic acid) dendrimers (Figure 8.8). Upon exposure with UV light, aqueous solutions of these triblock copolymers formed hydrogels that have potential for use as cartilage repair media, as a result of high water content allowing adequate diffusion of nutrients, oxygen and waste products in and out of cartilage cells. New cartilaginous material was grown successfully in the biodendrimer-based hydrogel scaffolds thus confirming these systems as promising new potential therapeutic agents.

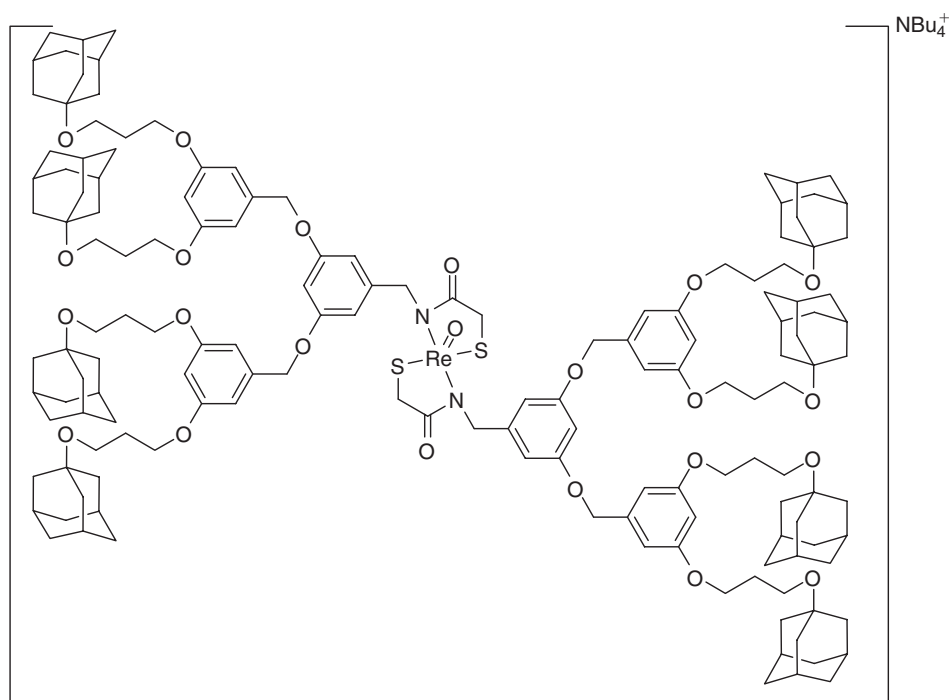
Two interesting dendrimer-based approaches to novel cancer therapeutics are the water-soluble adamantane terminated rhenium-cored aromatic polyethers, reported by Reinhoudt and co-workers [55], and the porphyrin-cored polyester-poly(ethylene glycol) dendrimer system described by Fréchet and co-workers [56].

The dendrimer featuring a rhenium core was solubilised by the complexation of the terminal adamantane groups by  $\beta$ -cyclodextrins generating a water-soluble complex with potential applications in radiotherapy (Figure 8.9).

The polyester-poly(ethylene glycol) dendrimer possessing a porphyrin core, described by Fréchet and co-workers, was designed as a novel photodynamic therapy agent. Photodynamic therapy agents generate cytotoxic singlet oxygen upon excitation by specific wavelengths of light. Current photodynamic therapy agents are activated by ultraviolet and visible light that is difficult to transmit through tissue and thus this technique is only applicable to surface tissues and not deep into an infected organ. A photodynamic therapy agent that could absorb and be activated by near-infrared light (which is transmitted

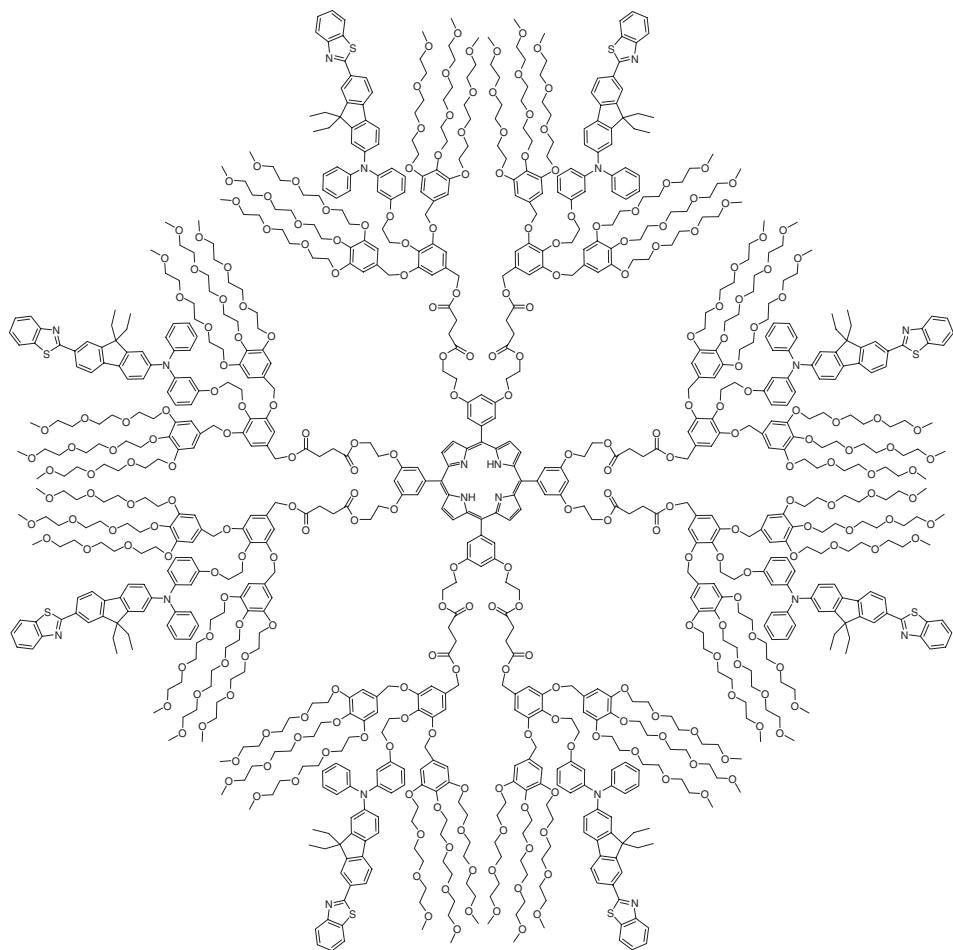


**Figure 8.8** The dendritic photo-crosslinkable cartilage repair agent developed by Grinstaff and co-workers [54].



**Figure 8.9** The rhenium containing dendritic substrate reported [55] by Reinhoudt and co-workers that has potential applications as a radiotherapy agent.

through tissue much more effectively) could be used for ailments that are situated deeper inside a body. Fréchet and co-workers have thus combined two-photon-absorbing chromophores with a multivalent porphyrin sensitiser and water-solubilising dendritic moieties (Figure 8.10).



**Figure 8.10** The porphyrin-based dendrimer described [56] by Fréchet and co-workers that has potential applications as a photodynamic therapy agent.

Chemical trapping and singlet oxygen luminescence experiments determined that singlet oxygen was being produced under IR irradiation conditions suggesting that there is great potential in this dendritic system to improve significantly the efficacy of photodynamic therapies as a weapon in the ongoing fight against cancer.

### 8.3 Dendritic metal nanoparticles

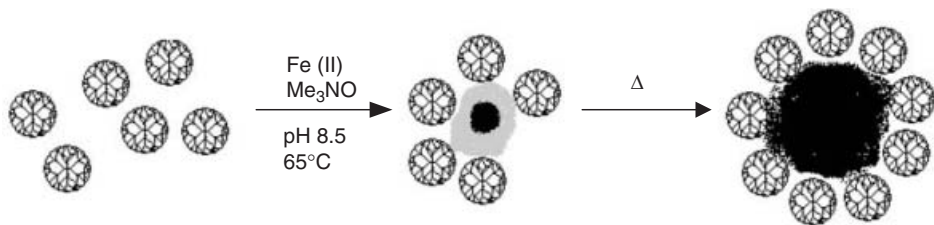
Metal nanoparticles exhibit interesting properties as a result of their intermediate size between bulk metal and ionic or atomic species. These properties make them attractive media for use in optical devices, medical technology, nanotechnology and, in particular,

catalysis due to their very high surface area to volume ratios. Dendrimers, with their unique globular architecture make excellent template materials for the generation and stabilisation of metal nanoparticles and indeed are now well recognised as suitable media for this application.

Water-soluble silver and gold nanoparticles have been produced by Dickson and co-workers [57] that were stabilised by second and fourth generation water-soluble hydroxyl terminated PAMAM dendrimers. These materials were found to exhibit a high quantum yield blue fluorescence emission. Consequently, the use of these gold nanoparticles as novel fluorophores is being investigated in optical devices such as optical storage media [58]. Silver and gold particles have also been described by Imae and co-workers that are stabilised by water-soluble amine terminated PAMAM dendrimers [59].

Reinhoudt and co-workers have also applied their adamantane/cyclodextrin solubilisation system to PPI dendrimers in order to synthesise and stabilise gold and platinum-based nanoparticles [60]. The nanoparticles were formed by the reduction of aurate or platinate anions in the presence of fourth or fifth generation dendrimers. It was proposed that the particles form inside the dendrimer assemblies as a result of electrostatic attraction between the nucleating anions and the polycationic core of the dendrimer. It was also postulated that the dense shell of adamantyl- $\beta$ -cyclodextrin complexes provides a kinetic barrier to the escape of the nanoparticles and stabilises them, thereby prolonging their lifetime. Another notable example of the synthesis and stabilisation of gold nanoparticles is the thiol terminated dendrimers developed by Crooks and co-workers [61]. PAMAM dendrimers with terminal groups either partially or fully modified with thiol moieties were both found to assemble in monolayers on the surface of planar gold substrates and affect the formation and stabilisation of gold nanoparticles. The high affinity of thiol groups for gold resulted in stable nanoparticulate composites that were isolable, and these assemblies have potential uses in sensing devices and catalysts.

Soluble iron oxide nanoparticles, stabilised with carboxylated PAMAM dendrimers, have been produced by Douglas and co-workers [62]. Oxidation of Fe(II) at slightly elevated pH (*ca.* 8.5) and temperature ( $\sim 65^\circ\text{C}$ ) in the presence of the carboxylated dendrimer resulted in the formation of highly soluble nanocomposites of iron oxide and dendrimer (Scheme 8.2).



**Scheme 8.2** A schematic representation of dendrimer mediated formation and stabilisation of iron nanoparticles [62].

SQUID magnetometry demonstrated that these crystalline materials exhibited superparamagnetism at room temperature whilst NMR spectroscopic relaxation studies revealed very high T1 and T2 relaxation times. These characteristics render these iron oxide/PAMAM dendrimer-based nanoparticles as promising prospects as a new class of MRI contrast agents.

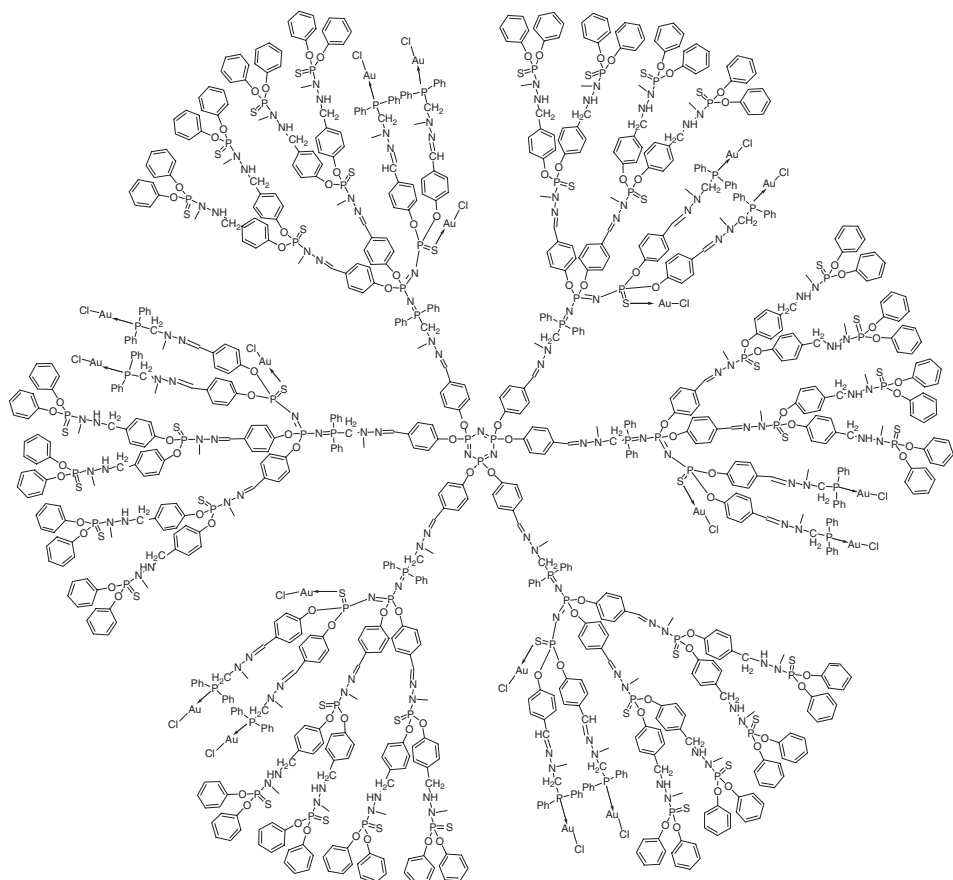
## 8.4 Dendritic catalysts

The unusual solubility and chemical properties of dendrimers have long been recognised with regard to use in catalysis. Multiple functionality at the peripheral end groups, within the dendritic branches and at the central core unit leads to possibilities for the incorporation of numerous catalytic active sites. Coupled to these approaches to dendritic catalysts, there is also potential for the encapsulation and solubilisation of catalytically active metal centres throughout the dendrimer skeleton. These characteristics, combined with the advantageous homogeneous reactivity of dendritic catalysts and their ease of separation, using product/catalyst isolation approaches employed with heterogeneous catalysts (such as nanofiltration), makes this new class of catalyst extremely attractive [63].

A notable example, that combines these beneficial aspects of hetero- and homogeneous catalysts, is the olefin dihydroxylation catalyst described by Fan and co-workers [64]. Whilst not strictly water-soluble, this system was soluble in a ternary mixture of solvents containing water, that phase separates into aqueous and organic layers upon the addition of excess water. The catalyst used was an osmium tetroxide-based system that featured dendritic ligands that rendered soluble the metal catalyst in a miscible mixture containing *tert*-butanol, acetonitrile, hexane and water (2:1:1:0.2 v/v, respectively). The homogeneous system catalysed the conversion of an olefin substrate into the corresponding diol – the addition of ~20% more water led to phase separation of the mixture thus allowing for efficient recovery of the catalyst in the organic layer whilst the desired polar diol remained in the aqueous phase.

A water-soluble hydroformylation catalyst was developed by Xi and co-workers [65]. Third generation PAMAM dendritic ligands, with hydrophilic amine or sulfonic acid end groups, were phosphonated and the rhodium complexes thus formed were found to catalyse efficiently the hydroformylation of 1-octene and styrene, under very mild conditions. Water-soluble dendritic cobalt phthalocyanines that exhibited catalytic activities and oxidised thiols in the presence of oxygen, have been synthesised by Kimura and co-workers [66]. The catalytic activity of the phthalocyanines was influenced by aggregation of the catalytic sites that results from strong intermolecular cohesive forces. It was proposed that steric isolation, enforced by the addition of a bulky dendritic 'coat' around the active phthalocyanine unit, could improve the catalytic activity. Acid terminated polyamide dendrimers were coupled to a phthalocyanine core to produce the desired water-soluble cobalt phthalocyanines, which were tested subsequently for catalytic activity and stability. The results obtained showed that the aggregation of phthalocyanines was reduced; the catalytic activity was improved and the stability of the catalyst was improved by addition of the dendritic substituents.

A novel application of dendritic catalysts has been described by Mendoza and co-workers. Water-soluble nickel containing dendrimers were found to catalyse the formation of multi-walled carbon nanofibres [67]. There is significant interest in the use of carbon nanofibres in applications such as flat panel displays and thus there is considerable research underway developing economical and scaleable production routes. Water-soluble hydroxyl terminated sixth generation PAMAM dendrimers were first used to deposit nickel nanoparticles onto a silicon surface. Vacuum annealing of the dendrimer film at 650°C and subsequent thermal growth under an acetylene and nitrogen atmosphere (at a pressure of 10 Torr) served to generate efficiently the desired multi-walled carbon nanotubes. Scanning electron and transmission electron microscopy revealed that a significantly higher



**Figure 8.11** The gold complexing phosphorus-based dendrimer with differentially branched arms that was described by Majoral and co-workers that has potential applications in catalysis [68].

uniformity of nanotube coverage was attained via this approach when compared to conventional carbon nanotube growth techniques.

Majoral and co-workers have published recently a comprehensive review on phosphorus containing dendrimers [68]. The synthesis, properties and applications of these materials as catalysts were covered in this article, ranging from unusual gold complexing dendrimers with differing branches (Figure 8.11) to the catalysis of hydroformylation or hydrogenation reactions.

## 8.5 Dendritic phase transfer catalysts

Phase transfer catalysts enable the reaction of insoluble materials and reagents to occur in solvents that would otherwise prove inaccessible. The ability to combine a hydrophobic core unit with hydrophilic peripheral moieties, or *vice versa*, render dendrimers highly suited



to applications as macromolecular phase transfer catalysts. The use of dendrimers as drug delivery agents (*vide supra*) exemplifies their use as solubilising agents and in the same manner, hydrophobic dendrimers that feature hydrophilic peripheral moieties can solubilise reactants or starting materials and act as reaction cavities for water-insoluble substrates.

Poly(alkyl aryl ether) dendrimers functionalised at the periphery with carboxylic acid groups [69] or phenol groups [70] have been employed in this capacity by Ramamurthy and co-workers. After the presence of a hydrophobic microenvironment within the dendrimer core had been established via pyrene solubilisation studies, photochemical reactions were carried out to assess the viability of the dendrimers as reaction cages or phase transfer catalysts. All of the photochemical reactions studied were carried out successfully in aqueous media, on compounds normally water insoluble, with increasing 'cage effect' observed for higher generation dendrimers. The viability of these dendrimer systems as photochemical reaction media was thus established.

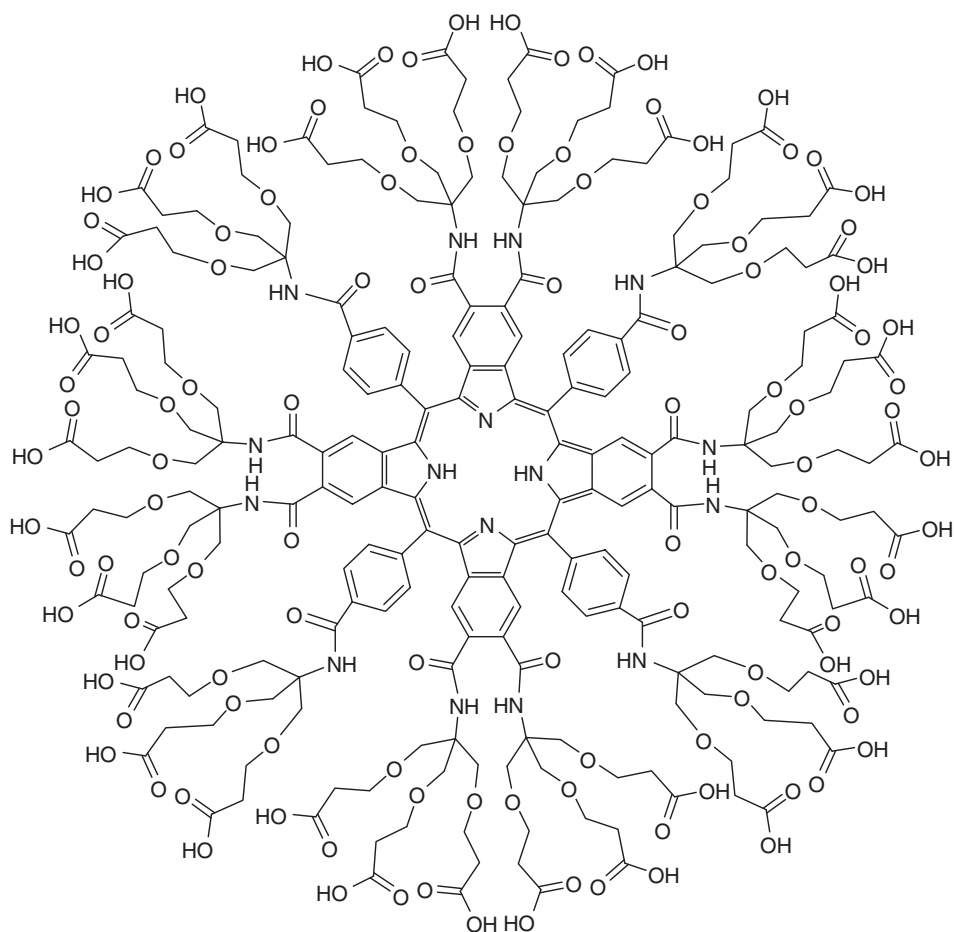
## 8.6 Dendritic sensor and indicator devices

The large number of peripheral surface groups present in dendrimers means that these hyperbranched macromolecules are suited to sensor applications. For example, Bazan and co-workers have functionalised the surface of PAMAM dendrimers with chromophores in order to obtain a light harvesting system that could be used for RNA/DNA detection [71, 72]. PAMAM dendrimers functionalised with phenylene-fluorene groups were synthesised, and amine salts present on the phenylene-fluorene groups rendered the dendrimers water-soluble. Fluorescence quenching and fluorescence resonance energy transfer experiments revealed that the higher generation dendrimers offered improved discrimination between hybridised and non-hybridised probe sequences and associated in a stronger fashion with double stranded DNA with respect to single stranded DNA. These water-soluble dendrimer systems provide an excellent tool for optically enhanced fluorescence DNA detection and may thus prove useful in biosensor applications.

A different approach to dendritic sensors involves modification of a sensor core unit with dendritic substituents to confer beneficial solubility properties. An example of a sensor core unit is the porphyrin macrocycle, a heterocycle that has been employed extensively in prototypical photochemical sensor systems. Vinogradov and co-workers have exploited the versatile photoactive porphyrin sensor unit as a fluorescence-based pH indicator for use in biological assays [73], by attaching acid terminated polyamide-ether dendrons as substituents (Figure 8.12). The two imino nitrogen atoms present in the free-base porphyrin are susceptible to stepwise protonation to afford initially a cation and then a dication, respectively. Upon protonation, both the emission and absorption fluorescence spectroscopic characteristics of the porphyrin core are subject to dramatic hypochromic shifts. This spectroscopic phenomenon formed the basis for an accurate pH indicator with potential applications in proton gradient determination studies in biological systems.

## 8.7 Dendrimer surfactants

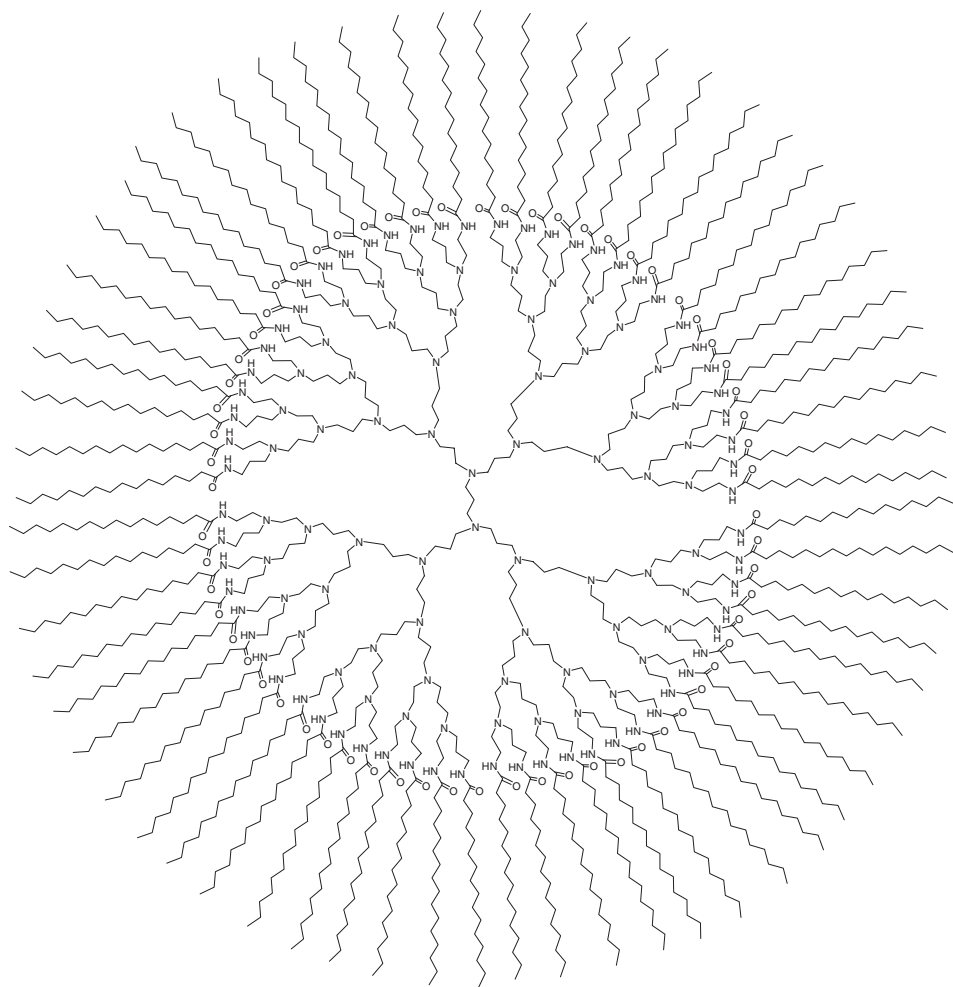
The unique architecture of dendrimers enables the functionalisation of the large number of peripheral end groups with moieties in order to confer very different and desirable



**Figure 8.12** The acid terminated porphyrin dendritic fluorescent pH indicator reported [73] by Vinogradov and co-workers.

properties upon the resultant macromolecule. As outlined previously, the addition of hydrophilic end groups to the peripheral surface of dendrimer that features a hydrophobic core can enable the solubilisation of a hydrophobic guest in aqueous media for use in areas such as drug delivery. An alternative application for amphiphilic dendrimers of this type, but employing hyperbranched macromolecules that feature the opposite configuration of hydrophilic and hydrophobic end groups, is as surfactants or unimolecular micelles.

Chapman and co-workers have appended *tert*-butoxycarbonyl terminated poly(lysine) dendrimers onto poly(ethylene glycol) chains [74] to produce dendritic block copolymer surfactant systems. The surfactant activity was explored by studies of the solubilisation of the dye Orange-OT in aqueous solutions and the dendritic copolymers were found to be effective surfactants. In a closely related study, Meijer and co-workers have synthesised poly(propylene imine) dendrimers that were modified with long hydrophobic alkyl chains, azabenzene units or adamantane groups (Figure 8.13) [75]. Studies of these PPI dendritic



**Figure 8.13** The poly(propylene imine) dendritic surfactant reported [75] by Meijer and co-workers.

derivatives indicated that in solvents of differing polarity, the long chain alkyl terminated dendrimers were able to undergo radical conformational changes ranging from globular inverted micellar structures to cylinders and that the dendritic PPI block acted as a polar head group while the hydrophobic units packed together. The long alkyl chain and azabenzene terminated dendrimers were dispersed into aqueous solutions – the higher generation dendrimers were stable in solution for several weeks and both PPI dendrimer derivatives were suitable for use as surfactants. However, in contrast, the adamantane terminated dendrimers could not be dispersed in water as a result of the persistent and rigid hydrophobic hyperbranched shell. The azabenzene terminated dendrimers also had the potential for use in non-linear optical applications and photoswitchable micelles. Arai and co-workers have also reported the synthesis of a water-soluble photo-responsive micellar system based upon dendritic polymers [76, 77].

## 8.8 Dendritic coatings

In the drive to reduce the use of volatile organic compounds (VOCs) in surface coatings and to ultimately generate waterborne paints, the coatings industry have examined dendrimers as a result of the highly functional nature and low viscosity of these macromolecules. However, it is worthy of note that the rigorous purification and synthetic approaches used in the production of dendrimers make them prohibitively expensive for large-scale applications such as coatings. As a consequence, irregular, and less perfectly branched hyperbranched polymers have been employed commonly in place of dendrimers since they can be synthesised in a one-pot approach. For example, a hydroxyfunctional dendritic polyaliphatic ester called 'Boltorn H20' has been used by Perstorp in conjunction with other additives to create a coating with a very low VOC content [78]. This preliminary study has shown that dendritic species are applicable in the coatings industry. The only objective advantage that dendrimers offer in this field is as research materials due to the possibility of the derivation of precise structure-property relationships.

Alkyd resins have proven beneficial additives to coating formulations as they have quick drying times and good surface properties. Mańnczyk and co-workers have produced hydroxyl terminated polyesters from the reaction of trimethylol propane and dimethylol propionic acid [79]. In addition, Lin and co-workers have also investigated hyperbranched polyol alkyd resins as materials for low VOC coatings [80]. Another notable example of a hyperbranched polymer that has found application as a coating material is the poly(ester amide) Hybrane™ that has been reported by DSM. Conventional papers have a surface that is too rough for high-speed printing. Application of a thin coating of the Hybrane™ polymer serves as a surface modification agent, in effect smoothing the surface and facilitating the printing process [81].

## 8.9 Selective dendritic complexation agents for heavy metal ions

The nuclear power industry and many other industrial applications increasingly employ heavy metals. The need, therefore, to decontaminate aqueous and organic waste streams is a growing problem that must be addressed. Effluent treatments include precipitation, evaporation, reverse osmosis and, more recently, polymer supported ultrafiltration in order to remove toxic heavy metal residues. The recovery of heavy metal ions from aqueous media is complicated by the fact that these ions must be removed in a selective fashion when present in low concentrations, from solutions containing much higher concentrations of other cations. Water-soluble dendrimer systems that are capable of binding heavy metals selectively have recently been investigated by several research groups. Schuster and co-workers have investigated the use of benzoylthiourea modified PAMAM dendrimers [82]. This dendrimer receptor system was found to act as a water-soluble chelating ion exchange material and selectively complex Co(II), Cu(II), Hg(II), Ni(II), Pb(II) and Zn(II) in the presence of competing complexing agents such as ammonia, tartrate, triethanolamine and sodium nitrate. In a similar fashion, Birnbaum and co-workers have employed PAMAM and poly(ethylene imine) dendrimers modified with ligands or hydrogen bonding groups [83]. These two dendrimer systems were modified with three types of receptor

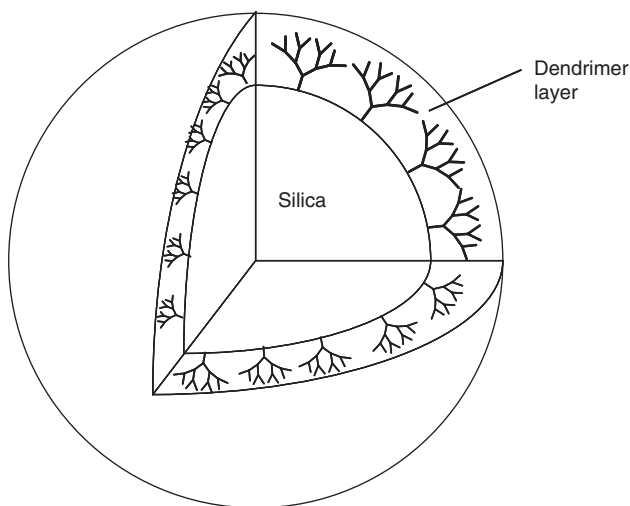
units: (i) alcohols, (ii) carboxylic acids and (iii) pyrazines to afford six dendrimers in total and were shown to be effective at complexing the oxyanions arsenate, chromate and phosphate, even in the presence of competing chloride ions. Cox and co-workers have employed PAMAM dendrimers, as an additive to silica sol–gels, to increase the level of doping of cobalt hexacyanoferrate. The dendrimer/silica sol–gel formulations doped with cobalt hexacyanoferrate were able to extract caesium ions from water, even in the presence of sodium ions. Leaching of caesium ions from the solid phase back into strongly acidic aqueous solutions was too low to be detected by ion chromatography. This study suggested that these inorganic–organic hybrid materials are promising as substrates for the solid phase extraction of caesium ions although further refinement of this technique is required.

## 8.10 Dendritic porogenic agents

Porogens are chemical entities that are employed to introduce porosity into cross-linked inorganic or organic network polymers. The globular and regular shape of dendrimers makes them ideal substances for applications of this type. Larsen and co-workers have used fourth generation PAMAM dendrimers as porogenic agents to produce cavities in amorphous silica xerogels [84]. The dendrimer-based porogens were found to possess superior stability in comparison to micellar alkylamine porogens [85] and, after calcination to remove the porogen, detrimental residues were not present (as observed when silicon alkoxide templates were utilised [86]). The resultant nanoporous materials possessed high surface areas ( $623 \text{ m}^2/\text{g}$ ) and thus have potential applications such as ion exchange media and catalysts supports.

Imae and co-workers also employed PAMAM dendrimers as porogens in the production of nanoporous silica [87]. As electronic devices attain increasingly small dimensions there is a need for more efficient insulators with extremely low dielectric constants in order to prevent electronic ‘cross-talk’ between microcircuits. Standard silicon insulators do not have sufficiently low dielectric constants and thus alternative materials are sought in this field. One of the most effective ways of reducing the dielectric constant is the introduction of porosity. Hydrothermal synthesis of dendrimer templated materials from tetraethyl orthosilicate at different dendrimer concentrations, pHs and temperatures, followed by calcination at 823 K under a flow of air to remove the dendrimer template, resulted in nanoporous materials. The morphology and particle sizes of the nanoporous silicon insulators were studied with transmission electron microscopy, scanning electron microscopy and infrared spectroscopy. These techniques revealed that the pores were in the size range of the dendrimer templates ( $\sim 4\text{--}5 \text{ nm}$ ) thus implying that the pores were generated via the imprinting of the individual dendrimer molecule within the silica matrix. Interpretation of these results led to the conclusion that PAMAM dendrimers are suitable templates with which to produce nanoporous silicas and could potentially be used to produce suitable materials for novel insulator applications.

Majoral and co-workers have utilised phosphorus containing dendrimers as porogens for the creation of porous metal alkoxides [88]. In a manner similar to the use of PAMAM dendrimer-based porogen templates, dendrimer containing pores were created after calcination to remove the dendrimers. Pores with dimensions ranging from 9 to 30 nm were created in the metal oxides, corresponding to either single dendrimers or dendritic aggregates, respectively, producing products with potential for applications such as highly absorbent materials.



**Figure 8.14** A schematic representation of a dendrimer coated silica particle that has been developed for use in size exclusion chromatography [89].

In a slightly different approach to inorganic–organic hybrids, dendrimers have been used to modify the pore sizes of chromatographic stationary phases as opposed to their use as porogens to create the porous network. Kunitake and co-workers employed PAMAM dendrimers to generate size exclusion chromatography columns with adjustable pore sizes [89]. The dendrimers appear to decorate the voids within the silica particles thereby reducing the exclusion limit molecular weight of a silica-based size exclusion chromatography column (Figure 8.14).

## 8.11 Hydrogels/gelators

Gel-type materials have been created in various solvents from a wide variety of organic compounds including the low molecular weight amphiphilic gelators described by Schmidt and co-workers [90] and urea-based organogelators, developed by Weiss and co-workers [91], that have been applied in the restoration of artwork. Reactive and functional gels have also been utilised in sensing applications [92, 93]. Dendrimers have also been studied to ascertain their ability to form stable gels. One of the first studies on dendritic gelators was carried out by Newkome and co-workers [94] with hydroxy terminated polyamide dendritic arborols. The hydroxy terminated polyamide dendrimers that featured a central alkyl chain were found to form thermally reversible aqueous gels in a concentration range of 2–10 wt.%. Zhang and co-workers have synthesised poly(*N*-isopropyl- acrylamide)/amine terminated PAMAM dendrimer hydrogels with potential for application in drug and gene delivery [95], Micic and co-workers have investigated the gelation of nitrocinnamate modified poly(ethylene glycol) dendrimers with potential for biomedical applications [96] and Majoral and co-workers have demonstrated the applicability of phosphorus-based dendrimers as gelators in aqueous media [97].

## 8.12 Other notable applications of water-soluble dendrimers

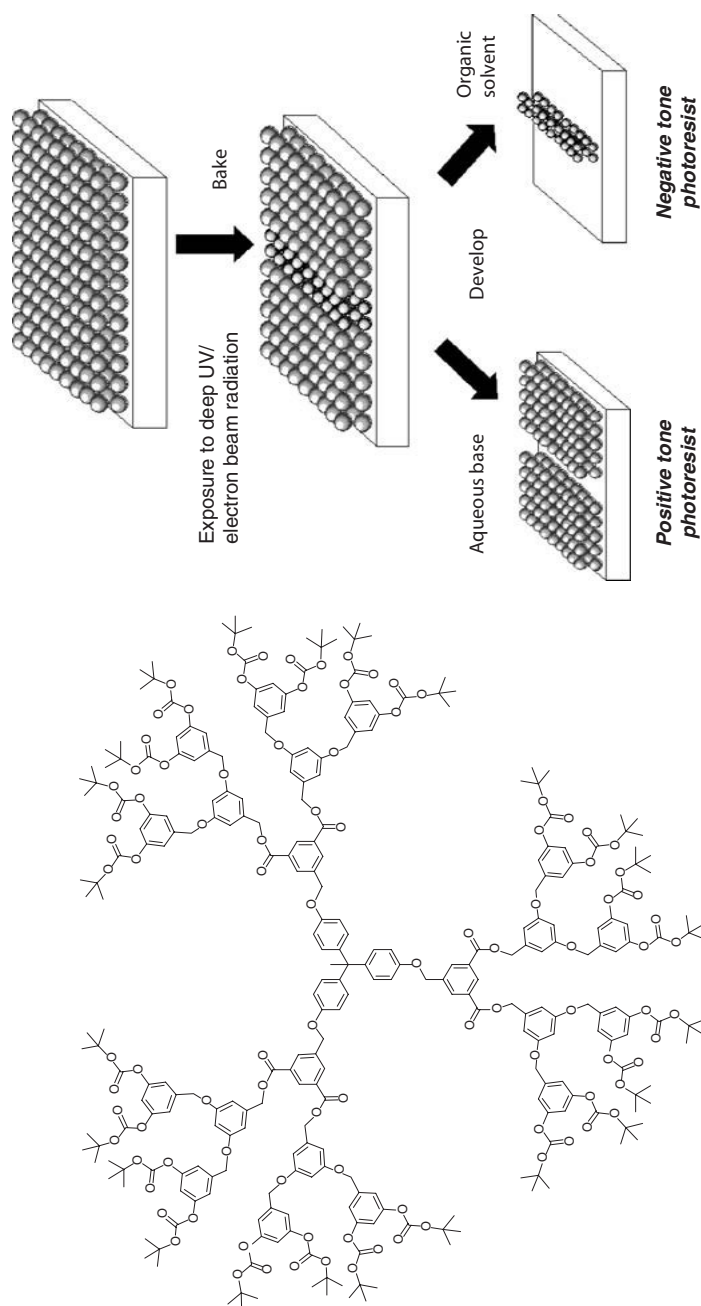
In addition to the proposed uses of water-soluble dendrimers already described, dendrimers have sought application in a range of other fields. For example, Goddard and co-workers have investigated the potential for the use of poly(aryl ether) dendrimers in fuel cell membranes [98]. Current fuel cell membrane technology uses a polymer electrolyte membrane that suffers from loss of water and thereby conductivity when operating at optimum temperatures ( $\geq 100^\circ\text{C}$ ). A dendritic diblock copolymer comprised of water-soluble acid terminated poly(aryl ethers) and hydrophobic poly(tetrafluoroethylene), was investigated as a potentially superior membrane material. The amphiphilic nature of the material was found to result in the formation of reverse micelle type nanoscale structures in which water forms a continuous nanophase. These materials were found to exhibit membrane properties for structure and transport comparable to the systems used currently at half the water content thus making them promising candidates for future use.

Fréchet and Tully have used poly(aryl ether) dendrimers, terminated with carbonate end groups as photoresists [99]. The aqueous insoluble carbonate terminated dendrimers were applied as a layer to a substrate. This dendritic layer was exposed subsequently to deep UV radiation or electron beam radiation and then baked to convert the masked areas of the dendritic carbonate coating to the deprotected and water-soluble polyphenoxide dendrimers by decarboxylation of the peripheral groups. The resultant deprotected polyphenoxide dendrimers exhibited differential solubility to the carbonate terminated dendrimers, which was exploited by removal of either the carbonate terminated or hydroxyl terminated dendrimer by washing with protic organic or aqueous solvents, respectively (Figure 8.15).

Majoral and co-workers have investigated phosphorus containing dendrimers by modifying the surface, core and structure in order to influence the thermal stability [100]. A large number of different phosphorus containing dendrimers possessing different generation numbers, core types and peripheral end groups were synthesised and their solubilities and thermal stabilities assessed. Third generation water-soluble cyclotriphosphazene dendrimers, that featured guanidinium end groups, proved to be thermally stable, were able to retain >95% of their mass up to  $275^\circ\text{C}$  and were postulated to have potential applications in biological systems and surface coating agents.

An interesting and novel potential use of dendrimers has been described by Menzel and co-workers who have developed photoluminescent dendrimers for fingerprint detection [101]. Amine terminated PAMAM dendrimer nanocomposites with cadmium sulfide were synthesised by the addition of methanolic solutions of cadmium nitrate and sodium sulfide to a methanolic solution of the dendrimer. Amine terminated dendrimers were selected so that they could form amide bonds with the carboxylic acids abundant in fingerprint residues. When bound to the fingerprint residues, the dendrimer composites serve as photoluminescent markers that aid detection.

Another interesting application of water-soluble dendrimers has been described by Stoddart and co-workers and utilises ferrocene containing carbohydrate dendrimers [102]. A ferrocene core substituted with glucopyranosyl residues was found to form complexes with  $\beta$ -cyclodextrin and has formed the basis for a supramolecular switch.



**Figure 8.15** A carbonate terminated poly(aryl ether) dendrimer that was studied by Fréchet and Tully as a potential photoresist material [99].



## 8.13 Conclusion

The wide variety of applications of water-soluble dendrimers outlined in this chapter demonstrates clearly the potential impact of these hyperbranched macromolecules in materials science. Synthetic studies have served to generate numerous dendrimer types in efficient ways via the application of convergent and divergent approaches. Only in recent years have applications been found that take advantage of the unusual and interesting chemical and physical properties that these materials possess. In particular, the significant number of publications in the medical field, especially reports that describe new drug delivery devices, reveal that dendrimers have great promise in this area. The wide range of unusual and interesting applications of water-soluble dendrimers that have also been described in this short review demonstrate the versatility of this sub-class of macromolecules and suggests that many more uses will be developed in the near future.

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## Chapter 9

# Preparation, Properties and Applications of Colloidal Microgels

*Louise H. Gracia and Martin J. Snowden*

### 9.1 Introduction

A smart material may be broadly defined as any material that can respond to subtle changes in environmental conditions, for example a change in temperature, pH, ionic strength, solvency or the influence of an applied electric field [1, 2]. One class of cross-linked polymers, often given the prefix of 'smart' or 'intelligent' materials, are colloidal microgel particles. These particles have been described as 'smart' due to their ability to undergo, quite often dramatic, conformational changes in response to a change in their environmental conditions. Microgel particles have a high degree of sensitivity and they are capable of undergoing a conformational transition (volume phase transition, VPT) which brings about rapid changes in their physical properties including changes in particle size and surface charge density. The rapidity of change comes about as a result of microgel particles having very high surface area to volume ratios which allows rapid diffusion of a given stimulus (e.g. a reduction in environmental pH), to facilitate a response throughout the matrix of a microgel over very short time scales, typically of the order of a few seconds. This property has enabled particles of this type to find many potential applications in the biomedical and industrial sectors. This article aims to give the reader an understanding of how microgels may be prepared by both established and novel methods by outlining some synthetic strategies employed for microgel synthesis. Methods used to characterise microgel dispersions and physico-chemical properties exhibited by basic and more complex dispersions will also be examined. Further we will provide an overview of the diverse number of applications for which microgels may potentially find utility.

Colloidal microgels may be defined as a disperse phase of discrete polymeric gel particles, which are typically in the size range of 1 nm–1  $\mu$ m uniformly dispersed in a continuous solvent medium [3]. Microgels are dispersions of particles – in contrast to true single-phase solutions – and as such they often display typical colloidal characteristics (e.g. turbidity). They are of considerable academic and commercial interest because of their 'sponge-like' properties and their ability to change molecular conformation, that is shrink and swell in response to a number of different external stimuli. Microgels have similar properties to polymers and water-swollen gels (usually termed hydrogels or macrogels) but are discrete particles which characteristics that are dependent on the method of synthesis, cross-link density, monomer concentration, monomer composition and solvency conditions [4].

## 9.2 Microgel preparation

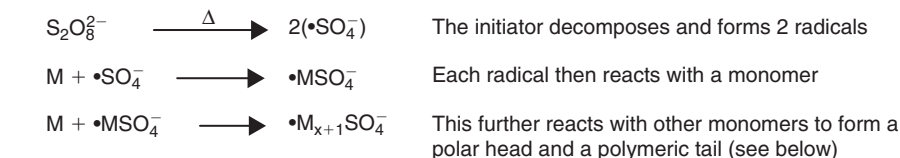
Several methods have been reported for the synthesis of microgel particles, these include emulsion polymerisation (EP) [5, 6], inverse EP [7], living free-radical polymerisation [8, 9] and synthesis by radiation [10, 11].

### 9.2.1 Emulsion polymerisation

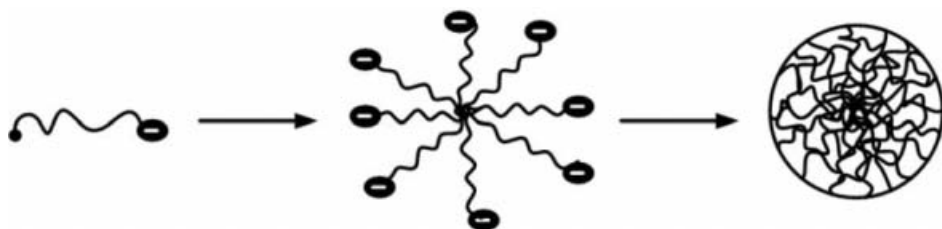
The most widely used method of synthesis for the preparation of microgel particles is EP [12, 13]. EP is a versatile technique which yields narrow particle size distributions and can be performed in the presence or absence of added surfactant, the former being conventional EP, and the latter being surfactant-free emulsion polymerisation, SFEP. Conventional EP enables preparation of very small microgel particles (i.e. particle diameters less than  $\sim 150$  nm) as surfactant molecules inhibit the particle growth. An obvious problem with this technique is the difficulty of completely removing residual surfactant, a problem which is not encountered when employing SFEP. The seminal work on SFEP was performed by Goodwin *et al.*, who used the technique to prepare non-swollen polystyrene latex particles [14]. In the SFEP method, the continuous phase must have a high dielectric constant (e.g. water) and ionic initiators are employed (e.g.  $K_2S_2O_8$ ). The charged polymer chains formed during polymerisation act as surfactant molecules and stabilise the growing particles. SFEP doesn't have the risk of surfactant contamination and is widely used for microgel preparation. EP and SFEP can typically produce a range of microgel particle sizes from  $<100$ – $1000$  nm.

*N*-isopropylacrylamide (NIPAM) is the major building block for temperature sensitive microgels; in aqueous solution it undergoes rapid free-radical polymerisation to give high molecular weight polymers. The first account of poly(NIPAM) microgels reports the SFEP of NIPAM with a cross-linking monomer [15]. The method is now a standard synthesis method for NIPAM based microgels and has been extensively studied for the preparation of poly(NIPAM) [12]. Typically, NIPAM is polymerised in the presence of a potassium persulphate initiator and cross-linking monomer containing two vinyl groups (usually *N,N'*-methylenebisacrylamide, BA) at a temperature of  $\sim 70^\circ\text{C}$  and under an inert atmosphere of nitrogen. The elevated reaction temperature is used firstly to initiate the decomposition of the initiator to form free radicals, but is also required so that growing poly(NIPAM) chains undergo phase separation to form colloidal particles. The particles gradually swell when the temperature is decreased with the maximum degree of swelling occurring around  $32^\circ\text{C}$ ; this avoids the need to transfer the particles from a poor to good solvent after preparation. This simple procedure can produce very uniform particle sizes, the diameter of a poly(NIPAM) microgel particle produced via SFEP is normally of the order of  $\sim 700$  nm. This reaction procedure can be found described in many sources [16,17,18,19].

Figure 9.1 illustrates the salient features of SFEP. Thermal decomposition of the ionic initiator ( $S_2O_8^{2-}$ ) initiates free-radical polymerisation. The oligomers produced are surface active and form nuclei when their length exceeds the solubility limit of the solvent. The nuclei then undergo limited aggregation, thereby increasing the surface charge until electrostatic stabilisation is achieved. Further particle growth occurs through absorption of monomer and/or oligomeric chains. This process results in a decrease in the concentration of oligomers to below the critical value required for particle formation. Polymerisation



These then aggregate into discrete particles



**Figure 9.1** Schematic illustrating the various steps during the preparation of a microgel via SFEP.

continues within the particles until another radical species enters the growing particle and termination occurs. A significant amount of cross-linker is usually used for the synthesis of microgels (approximately 10 wt.%). For such cases, the probability of causing a cross-linking reaction for a growing chain is high from the beginning of the polymerisation. A newly formed primary chain tends to be cross-linked with the existing polymer molecule sequentially, and as a consequence, each polymer particle essentially consists of one single cross-linked polymer molecule, once stable polymer particles are formed. The key feature of SFEP is that the particle nucleation period is very short (of the order of minutes) which ensures a narrow particle size distribution.

There are problems encountered in microgel synthesis by EP methods [20], these include:

(1) *Microgel cleaning*

The generation of significant quantities of sol (linear polymers) during the SFEP and EP which can be difficult to remove and can only effectively be done so by ultracentrifugation and re-dispersion of the microgel. Membrane processes, such as dialysis, have been deemed ineffective for the cleaning of poly(NIPAM) microgel as they cannot remove high molecular weight sol components. The surfactant employed in EP is also difficult to remove and can effect the physico-chemical characteristics of the microgel if left behind (sodium dodecyl sulphate (SDS) effects the swelling characteristics of poly(NIPAM) [21]). It has not been proved that SDS found to be bound in microgels [22] can be removed completely from the final product.

(2) *Particle size produced*

Small particles (<50 nm) cannot be produced by SFEP as there is not sufficient available to stabilise high concentrations of small particles. EP can produce smaller particles, but not cleanly.

(3) *Volume fraction produced*

Microgels are usually produced at 5 wt.% polymer, much less than commercial latex dispersions (30–60 wt.%)

#### (4) *The morphology of microgel particles produced*

NIPAM and BA are shown to be consumed at different rates during synthesis resulting in possible non-uniform composition within particles [23]. Further discussion of this aspect of microgel properties can be found later on in this article (see Section 4.8 entitled 'Microgel Structure')

It has been established that monodisperse poly(NIPAM) particles may also be formed via SFEP in the absence of added cross-linking monomer. It has been observed that NIPAM can self-cross-link into microgel particles through tert carbon atoms both during and after the polymerisation of NIPAM monomers, the resulting microgel particles are stable and resemble BA cross-linked microgel particles [24]. However the efficiency of cross-linking is clearly improved when cross-linking monomers are employed. Reaction conditions and characterisation of self-cross-linked microgels can be found elsewhere [25].

### 9.2.2 *Inverse EP*

An advantage of EP is that inverse emulsions (water in oil) can be produced. Non-continuous-phase polymerisation is important from both industrial and academic viewpoints. Conventional EP, as already outlined, is useful for producing polymer latex products, which have diverse applications but inverse EP is also of general interest. The topic has been widely studied and investigated to investigate both the fundamental science involved and its potential uses. Inverse EP methods have been recently employed to develop a DNA carrier used to immobilise an enzyme [26] and to polymerise a gel that has unique rheological properties [27]. Inverse EP could be employed in situations that involve the polymerisation of monomers that have high solubility in water with high viscosities, which usually present significant practical difficulties. It is believed that the use of inverse EP would obviate such problems [28, 29].

Neyret and Vincent [30] have developed such an approach for the formation of microgel particles, named inverse microemulsion polymerisation. The oil phase consisted of anionic 2-acrylamido-2-methylpropanesulfonate (AMPS) and cationic (2-(methacryloyloxy)ethyl) trimethylammonium (MADQUAT) monomers in addition to a BA cross-linker. The co-polymerisation was initiated using UV irradiation and the product isolated and re-dispersed in aqueous electrolyte solution to yield polyampholyte microgel particles. The particles became swollen in the presence of high electrolyte concentrations as a result of screening of the attractive electrostatic interactions between neighbouring chains.

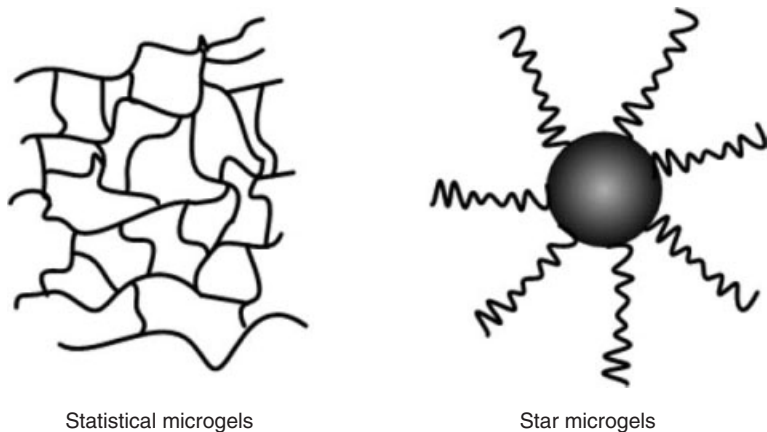
A second study employing this technique used novel inverse microemulsion polymerisation to produce microgels suitable for novel viscosity thickeners [7]. The thickening effect of microgels was shown to be an effect of particle size [31], the smaller the particle, the more effective its ability as a thickener, control of the particle size during synthesis is therefore an important issue for such applications. The purpose of the study conducted by Kaneda *et al.* was not only to produce a microgel suitable as a thickener but to also produce a microgel of minute size, the inverse microemulsion polymerisation method was deemed a suitable synthesis method for such microgels. They employed a non-ionic surfactant which when in together with a ternary system results in a 'phase inversion phenomenon,' which results in a phase inversion from oil/water to water/oil. When this phase inversion occurs (at the hydrophilic lipophilic balance (HLB) temperature [32]) a transparent low



viscosity phase appears which is a reversed micelle solution. This phase consists of micelles swollen by water and is therefore an ideal environment to accommodate water-borne polymers in a confined space. This 'confined space' method of synthesis allows a possible route to control microgel particles size in large scale production as the reverse micelle phase is thermo-dynamically stable. Experimental details can be found elsewhere [7]. The results of this study indicate that a cross-linked polymer of  $\sim 50$  nm can be produced in these confined spaces.

### 9.2.3 *Living free-radical polymerisation*

Living free-radical polymerisation is a recently developed technique for the controlled polymerisation of vinyl monomers. The significant advantages of this technique permits the preparation of a wide range of different materials which are either difficult to prepare, or not available via other polymerisation processes. For example, the architecture or topology of the polymer, composition of the backbone and inclusion of functionality can all be readily manipulated using 'living' free radical methodologies while still retaining a high degree of control over the molecular weight and polydispersity of the product. Staudingar and Husemann [33] found that the free-radical polymerisation of dilute solutions of divinyl or vinyl/divinyl monomer led to the formation of macromolecules with vinyl pendant groups. These groups could undergo random intermolecular/intramolecular cross-linking to form statistical microgels which have a random distribution of cross-links and lack structural control due to irreversible termination steps. Star microgels exhibit the opposite characteristic and have a high degree of structural control (Figure 9.2 illustrates the difference between statistical and star microgels). They are usually found to comprise of a series of linear arms held by a central cross-linked core. They can be prepared via anionic polymerisation with cross-links introduced by the living nature of the polymer chain [34]. It has been found that living free-radical polymerisation provides a much better control over the formation of statistical microgels than traditional free-radical polymerisation and can be used successfully for the synthesis of statistical and star microgels [35] using divinyl monomer, which previously posed the



**Figure 9.2** Schematic illustrating the structural differences between statistical and star microgels.

problem of gelation during tradition polymerisation. The method is reported to allow better control over the molecular weight properties of the polymers and have great potential for the synthesis of star microgels with varying properties.

Star microgels have also been produced using a living linear polymer as the arms of the microgel structure, which were prepared first. The living polymer was then reacted with a divinyl cross-linker to form a star microgel consisting of a central core and surrounded by linear polymeric arms. Experimental details are reported elsewhere [8].

### 9.2.4 Radiation polymerisation

Radiation has been employed for the synthesis of various microgel dispersions. P Ulanski *et al.* [11] exposed an aqueous solution of linear poly acrylic acid (PAA) to pulse irradiation produced by fast electrons. The irradiation energy facilitated the formation of PAA radicals and these radicals underwent a major reaction path of intramolecular recombination. This reaction led to an interlinking process within the polymer molecules and the final formation of nano-gel particles.

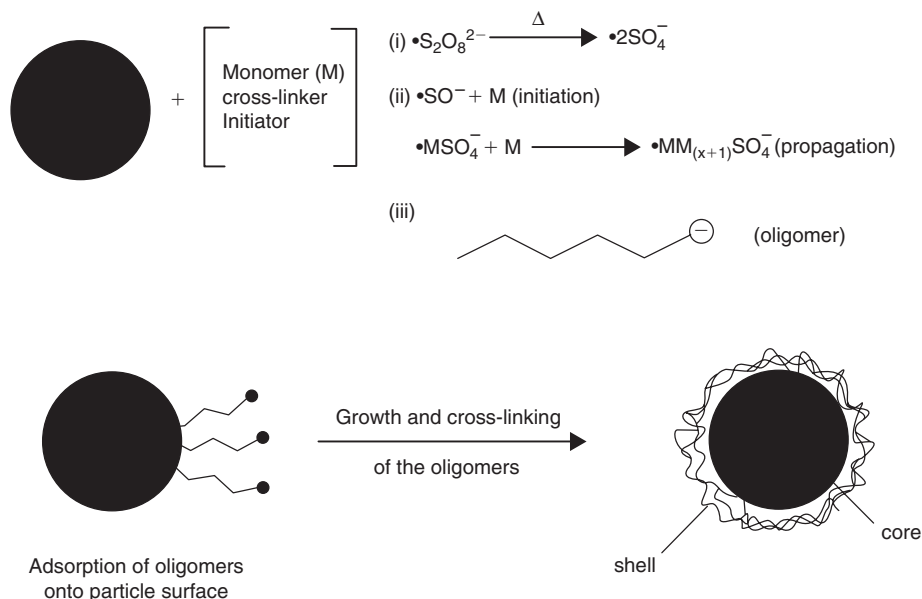
H Sun *et al.*, used UV radiation in the preparation of a novel magnetic nanogel [36]. Acrylamide monomers were mixed with a  $\text{Fe}_3\text{O}_4$  nanoparticle dispersion. BA was added as the cross-linking agent. The solution was then exposed to UV light. The polymerisation reaction took place at room temperature. The result took the form of magnetic core-shell nanoparticles containing  $\text{Fe}_3\text{O}_4$  as the core.

Another example of the application of irradiation in microgel synthesis is given by Giammona *et al.* [37],  $\gamma$ -rays are used to synthesise bio-compatible microgels based on a purified high guluronic acid alginate (PHG) co-polymer. Since these microgels are aimed at medical applications, the use of  $\gamma$ -rays brings about the extra advantage of sterilisation upon preparation.

### 9.2.5 Synthesis of core-shell microgels

The versatility of microgels can be enhanced by the preparation of a core-shell particle structure with varying properties of core and shell components. Core-shell particles normally consist of an insoluble latex particle surrounded by a gel layer, with overall characteristics having contributions from both components. Poly(NIPAM) coated latex particles were first reported by Pelton [38], who carried out the synthesis by SFEP below the lower critical solution temperature (LCST) of NIPAM to prevent the occurrence of phase separation. A two-step SFEP synthetic strategy has also been employed [39, 40] preparing latex and NIPAM particles which were used as nuclei for subsequent polymerisation. Recently core-shell particles have been produced using a poly(NIPAM-AA) co-polymer as either the core or shell resulting in multi-responsive core-shell particles sensitive to both temperature and pH, with a higher volume phase transition temperature (VPTT) than exhibited by NIPAM alone. These particles were also prepared by a two-step EP method [41–43].

Other particles consisting of a core of polystyrene surrounded by layers of poly(NIPAM) and poly(NIPAM-co-AEM) were prepared by Nabzer *et al.* [44]. The particles were synthesised by first producing a polystyrene core via a SFEP reaction and then when the core was approximately 90% completed, the shell was generated by the addition of NIPAM/



**Figure 9.3** The outline of a possible synthetic route for the synthesis of core-shell microgel particles.

aminoethyl methacrylate monomer and a BA cross-linker were added. The thickness of the shell surrounding the core was controlled by changing the environmental temperature of dispersion with the shell collapsing at a temperature above the LCST for poly(NIPAM). The resultant particles via this process were found to be monodisperse. The mechanism outlining the formation of core-shell particles is illustrated in Figure 9.3.

## 9.3 Characterisation of microgels

Numerous methods have been used in microgel characterisation. Many of these methods have their own merits and shortfalls. In order to acquire a comprehensive understanding of the properties of microgels different analytical measurements need to be made. For example, in a study of a poly(NIPAM) microgel [45], the swelling behaviour is monitored by combination of dynamic light scattering (DLS) and scanning electron microscopy (SEM); while the information of local structure and dynamics is obtained from small-angle neutron scattering (SANS) and verified by atomic force microscopy. Some of the most important and widely used microgel characterisation methods in the literature are briefly introduced below.

### 9.3.1 Dynamic light scattering

DLS is a widely used experimental method for examining microgel size and shape and has been used to monitor the temperature-induced swelling/de-swelling process. It is therefore a particularly useful technique to monitor the conformational behaviour of microgels in different solvent environments.

This well-established technique measures the diffusion coefficient of particles through the decay of the intensity of the correlation function. To convert the measured diffusion coefficient ( $D$ ) into particle diameter, the Stokes–Einstein relationship is used (equation (9.1)):

$$D = \frac{kT}{6\pi\eta a} \quad (9.1)$$

Here,  $T$  is the temperature,  $k$  the Boltzmann constant,  $\eta$  the viscosity of the solvent, and  $a$  is the diameter of a hydrodynamically equivalent sphere. For an ideal dilute solution of non-interacting particles  $D$  corresponds to the self-diffusion coefficient [45].

Numerous experiments have sized microgel particles by SEM, transmission electron microscopy (TEM) and DLS with good agreement between the methods. This implies that the Stokes–Einstein relation is a pretty good estimate for the diffusion coefficient, at least in the collapsed state. For swollen particles, TEM and SEM are no longer applicable since the drying process, required to carry out such techniques, causes collapse of the microgel and can lead to erroneous images. DLS then becomes the only sizing method available. A study by Routh *et al.* [46] confirms that DLS is a reliable method for microgel particle size measurement. The Darcy number ( $Da$ ), which quantifies the effect of the particle permeability and the diffusion coefficient, is estimated to be on the order of  $10^{-7}$ . As microgel swell, the particles' permeability will certainly increase and the Darcy number will consequently increase as well. However, the Darcy number is less than 0.03 (still much less than unity) even for highly swollen microgel particles. This tells the reader that the solvent will not stream through the microgels and hence will not inhibit or alter the diffusion, meaning diffusion is a reliable parameter to measure.

There are numerous reports in the literature where DLS has been used to follow the collapse of the colloidal microgel particles across the VPT [45, 47]. By comparing the hydrodynamic diameter before and after the transition it is possible to determine the swelling ratio of the microgel.

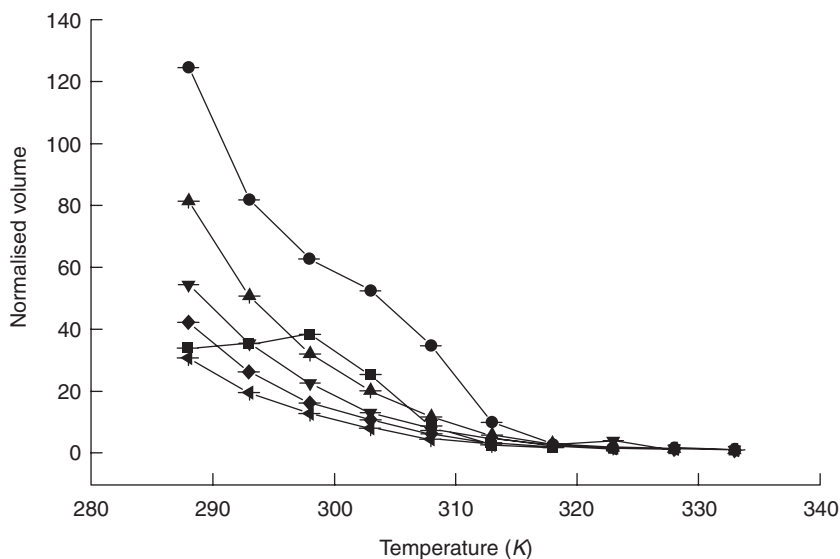
Snowden *et al.* [47] studied the swelling behaviour of poly(NIPAM-4-vinyl pyridine) (poly(NIPAM-4-VP)) microgels. DLS shows that the ability of the particles to swell reduced (observed as the decrease in the absolute volume of the particles in the swollen state) by increasing the 4-VP mole fraction. However, the particle size in the collapsed state is only negligibly affected by the introduction of a co-monomer. The final volumes of all the microgels in this study are almost constant from 320 to 330 K. This observation suggests that the final collapsed volume of the particles is a property of the polymer itself. The change in microgel swelling behaviour becomes more apparent if the volume data is normalised (Figure 9.4).

### 9.3.2 Small-angle neutron scattering

Small-angle neutron scattering (SANS) is a structural probe, commonly employed to study colloidal systems of 1–500 nm. It has been used to study the internal structure of the microgel particles by a number of research groups [45, 48, 49].

Neutron scattering results from a short-range repulsive interaction between the neutrons and nuclei of a material. The SANS experiment involves the measurement of the scattered intensity,  $I(Q)$ , of a neutron beam with a wavelength,  $\lambda$ , as a function of the scattering vector,  $Q$ .

Because of the presence of the cross-links, microgel particles do not have a uniform density at the length scales of the neutron wavelength. Mears *et al.* [50] were the first to examine



**Figure 9.4** Plot of normalised volume change as a function of temperature, ■ poly(NIPAM), ● 0.148, ▲ 0.246, ▼ 0.342, ◆ 0.436, ◄ 0.531, mole fraction of cationic poly((NIPAM)-co-4-VP).

poly(NIPAM) microgel particles in the presence of SDS using SANS. They reported that in the presence of the microgel at concentrations just above the critical micelle concentration (CMC), the surfactant existed as small; polymer bound aggregates of less than five monomer units, rather than larger micelles. This is in stark contrast to other homopolymer/surfactant systems such as SDS/poly(ethylene oxide) where the polymer bound micelles have structures similar to free micelles obtained without polymer. They also reported the increase in particle swelling in the presence of SDS.

Temperature-dependent SANS measurements can provide information about structural changes across the VPT. SANS has been employed to investigate the structural changes for poly(NIPAM) particles across the VPTT [48] and as a result of thermally induced de-swelling, osmotic de-swelling and co-non-solvency [45]. It has been shown that poly(NIPAM) particles subjected to osmotic de-swelling and co-non-solvency appear to have a more diffuse network structure than pure particles heated to 50°C. The morphology of the colloidal poly(NIPAM) microgel particles with different cross-linker density has been also investigated by SANS.

SANS is also a valuable tool which can be applied to the determination of the structure of a microgel particle with respect to the distribution of a cross-linker density throughout the particle [12] and monomer distribution within the particle.

### 9.3.3 Turbidimetric analysis

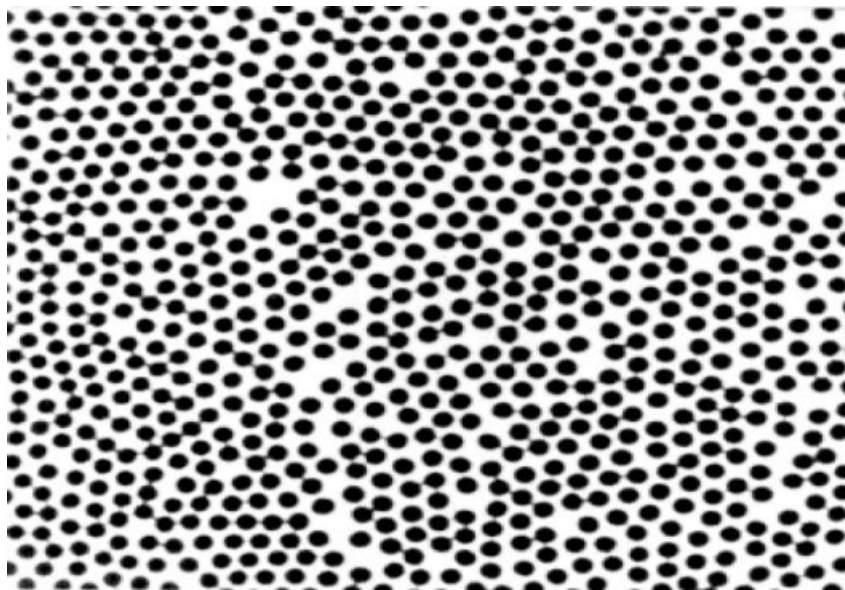
Turbidimetric analysis is a valuable technique for determining the temperature dependence of the conformational transition of the microgel dispersions and is performed using UV-visible spectroscopy [51, 52]. It is also used to monitor the effect of pH, concentration, hydrophobic and hydrophilic content of the microgel on the turbidity of the dispersion [53].

The turbidity of microgels is largely dominated by the amount of water contained within the interstitial regions between cross-linked polymer chains as this controls the difference in refractive index between the microgel–water macrocomplex and the bulk water. As temperature increases up to a certain point, water contained in the microgels is expelled from the microgels due to the disruption of H-bonding between water and the hydrophilic amide groups and the hydrophobic association interactions between isopropyl groups, leading to the increase of the refractive difference between solvent (water) and microgels [51].

### 9.3.4 Other techniques

TEM has been widely used to study microgel dispersions [45, 54, 55]. The use of electron microscopy in studying microgels has been reported in various sources [56]. This technique offers the advantage of studying a real image that illustrates both the size and shape of the particles. In the electron microscopy chamber the microgels are exposed to high vacuum conditions and as a result the microgel particles become deformed and form pancake like structures thus misrepresenting their hydrodynamic shape which is much more spherical. Pelton [5] first reported that poly(NIPAM) particles exhibit a pronounced tendency to form ordered structures when deposited on TEM grids and it was found that TEM data cannot be used to obtain accurate measurements of the particle size for particles deposited from the swollen state. The typical TEM of poly(NIPAM) microgel particles is shown in Figure 9.5.

Isothermal titration calorimetry (ITC) has been employed to investigate the thermodynamic parameters associated with the interactions between polymer systems in solution and other solvents [57]. Other studies employing ITC, carried out recently, have examined the interactions between poly(NIPAM) microgels and amino acids [58] as well as SDS [59].



**Figure 9.5** TEM of poly(NIPAM) microgel particles. The average particle diameter was 450 nm.

Nuclear magnetic resonance (NMR) spectroscopic analysis is another useful technique for the characterisation of microgel particles. The technique provides information regarding the internal environment [60, 61] and thermoresponsive transition behaviour of a microgel [62].

Poly(NIPAM-co-vinyl laurate) (poly(NIPAM-co-VL)) co-polymers were prepared at various feed ratios via conventional radical random co-polymerisation. The formation, composition ratios and molecular weight of co-polymers were examined. The thermoresponsive behaviour of poly(NIPAM) and poly(NIPAM-co-VL) solutions at low and high concentrations were intensively investigated by turbidity measurement, micro-differential scanning calorimetry (Micro-DSC), temperature-variable state fluorescence, <sup>1</sup>H NMR and DLS [62].

DSC can be applied to study microgel systems that undergo a thermally induced VPT. The VPT of NIPAM at 34° can be monitored by this technique. The instrumental output is an endotherm for the heating cycle and a mirror image exotherm for the cooling cycle. As the microgel is heated a series of processes begin to take place. The major contribution to the calorimetric output is the expulsion of water from regions surrounding the polymer chains. This breaking of the polymer–solvent interaction is an endothermic process. In addition to the expulsion of water from the microgel structure some aggregation of the polymer chains will inevitably take place as the microgel structure collapses. From the calorimetric output information regarding the enthalpy change associated with the VPT the precise temperature at which it occurs and some detail regarding the extent of chain aggregation within the microgel may be obtained [60, 63]. DSC has been widely used in the studies of poly(NIPAM) solution transition [60, 64, 65]. Figure 9.6 shows a typical DSC output for a poly(NIPAM) microgel dispersion, undergo a thermal conformational transition at 34°C in water.

Thermoresponsive transition behaviour of hydrophobically modified NIPAM co-polymer (poly(NIPAM) and poly(NIPAM-VL)) solutions at low and high concentrations were intensively investigated by Micro-DSC. The result obtained has shown that incorporation of hydrophobic segment and solution concentration influence the transition peaks [62].

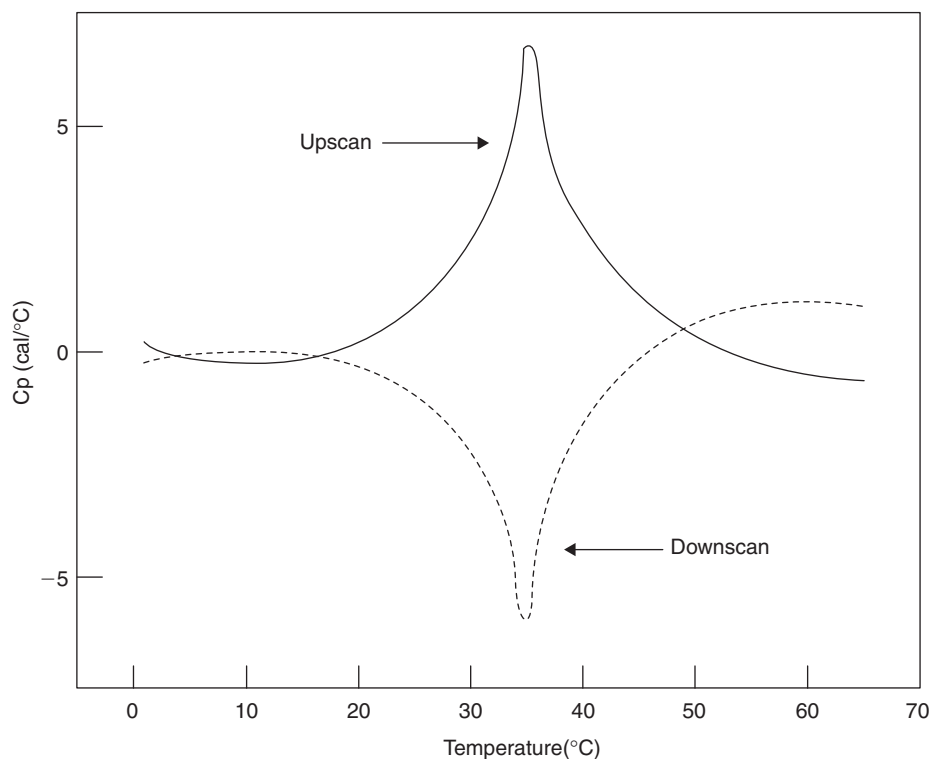
## 9.4 Properties and applications

Microgels differ from bulk gels in a number of fundamental ways. Some of these differences are illustrated in Figure 9.7 and include significant differences in for example bulk viscosity characteristics, rapidity of solution response and surface area to volume ratios. Whilst bulk gels and microgels have very similar polymer chemistry their physical molecular arrangement can give rise to the differences stated. The following discussion will focus primarily on microgels; however it is worth noting that some of the polymer chemistry behaviour described may be equally applicable to bulk gels as it is to microgels.

Microgels can be prepared which are sensitive to pH, electrolyte concentration, light intensity or the introduction of a co-solvent (non-solvent) to their environment.

### 9.4.1 Thermosensitive microgels

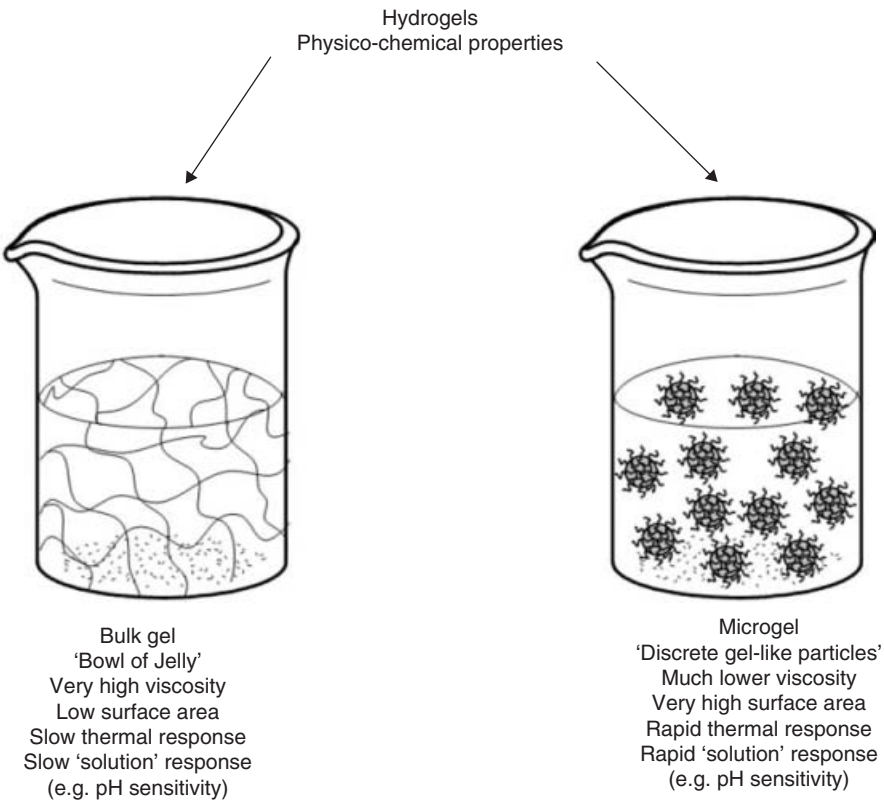
Poly(NIPAM) microgels are by far the most widely investigated and reported systems [5, 12, 66]. The first reported preparation of microgel particles of this type was by Pelton and



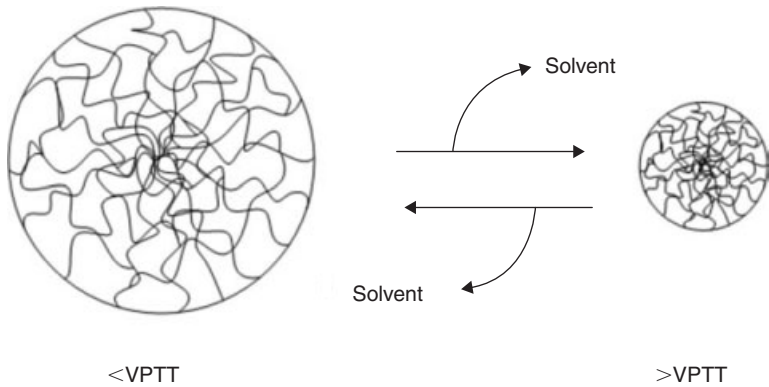
**Figure 9.6** A typical DSC output for a poly(NIPAM) microgel dispersion.

Chibante in 1986 [15], where they used a SFEP process to produce a dispersion of monodisperse microgel particles. The particles formed were of interest because they showed a thermo-reversible 'conformational transition' in water at around 34°C. Below this temperature the microgels have a swollen conformation as a result of low van der Waals attractive forces and hydrogen bonding, with the interstitial spaces of the microgel being filled with water molecules. When the environmental temperature of the dispersion approaches the transition temperature of 34°C, the polymer-solvent interactions decrease dramatically and the particles begin to contract. The polymer chains collapse as poly-polymer interactions dominate over polymer-solvent interactions. The polymer molecules now prefer to interact with themselves rather than with water molecules, and the hydrogen bonds that conferred stability are now disrupted. As the microgel shrinks, a high proportion of the entrapped water is excluded from the interstitial regions within the polymer matrix and the particle begins to form a hard sphere like structure (Figure 9.8). When the microgel particles are in their collapsed state, they remain dispersed as a result of electrostatic repulsion between charged groups (originating from the initiator) on the microgel surface. The shrinking of microgel particles is a reversible process so that on cooling back to below 34°C, the polymer-solvent interactions ameliorate and the microgel returns to its original swollen conformation.





**Figure 9.7** Illustration of the fundamental difference between micro and macrogels.



**Figure 9.8** Schematic illustrating the VPT of a thermosensitive microgel.

Microgels have an advantage over linear polymers and macrogels, which is the speed at which the conformational change occurs. The time taken for the equilibration of microgels is reported to be approximately 1 s [67, 68] which is much faster than the time taken for polymers and macrogels in solution, which can be in the order of hours or days. The

cross-linking of the polymer chains in a microgel means that the distance between polymer chains is a great deal shorter when compared with the distance between linear chains in solution. This characteristic gives rise to the speed at which the polymer chains collapse. The large surface area to volume ratio of microgels also aids rapid chain collapse, giving microgels the advantage over their macrogel and linear polymer counterparts.

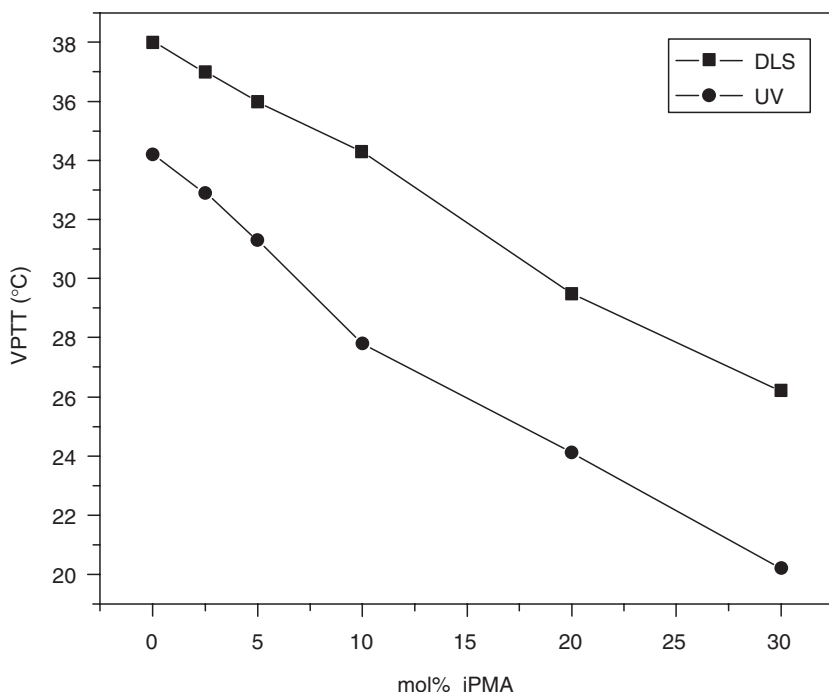
### 9.4.2 Effects of co-monomers

Non-NIPAM based temperature sensitive microgels have been prepared based on poly(*N*-ethylacrylamide) (poly(NEAM)) [69]. The NEAM monomer is less hydrophobic than NIPAM, this results in a higher transition temperature for poly(NEAM) microgels of 78.2°C in water. This illustrates the ability of microgels to be 'tailor-made' to exhibit the desired properties by changing the monomers used in their preparation. The combination of monomers which respond to different stimuli or have ranging hydrophobicities (therefore different LCSTs) is a method of generating microgel particles which exhibit physico-chemical characteristics which are composite of those of the co-monomers employed in synthesis. The addition of a small amount of a co-monomer (typically 1–5% w/w monomer) can have a dramatic effect on the overall properties of the resultant microgel particles. For example, a pH and temperature sensitive microgel can be prepared by co-polymerising NIPAM with AA [70]. The  $pK_a$  of the ionisable monomer will control the pH at which the microgel undergoes a conformational transition (see Section 4.3 pH sensitivity).

It is long established that the incorporation of a co-monomer with different hydrophilic or hydrophobic values into the linear NIPAM polymer influences its thermoresponsive behaviour. For example, the thermoresponsive transition behaviour of a poly(NIPAM-VL) co-polymer microgel was studied by Z Cao *et al.* [71]. Turbidimetric analysis proves that the hydrophobic VL moieties of the polymer chains lead to a significantly lower VPTT (20°C for higher content of VL in the microgel compared with 34°C for pure NIPAM dispersion, both at a concentration of 52.0 mg/ml). The VPTT of the hydrophobically modified poly(NIPAM) solution is also controlled by the dispersion concentration. The VPTT of the poly(NIPAM-VL) solution at 10.4 mg/ml is 22.5°C, shifting upward by 2.5°C from that of the 52.0 mg/ml dispersion. Moreover, the transition range is much broader relative to that of poly(NIPAM), spanning at least 10°C with the dispersion changing from clear to totally milky state. One explanation for this behaviour, which is generally applicable, is that incorporation of hydrophobic co-monomer could reduce the hydrogen bonding between the water molecules and the hydrophilic amide groups of the NIPAM microgels, thus, there are fewer hydrogen bonds to be broken as temperature increases. Hence less energy is needed to break the hydrogen bonds when compared with unmodified poly(NIPAM) microgels.

A poly(NIPAM/isopropyl methacrylate) (poly(NIPAM-iPMA)) microgel has been synthesised with varying monomer ratios and the effects of the co-polymer on the VPTT has been investigated by DLS and UV turbidimetric analysis [72]. Predictably, the VPTT of the hydrophobically modified microgels is lowered in both measurements. The extent of the VPTT decrease is dependent on the mole fraction of the iPMA co-monomer, as shown in Figure 9.9.

In this study, the VPTT of the poly(NIPAM) microgel is successfully tuned by the amount of incorporated iPMA.



**Figure 9.9** Dependence of the VPTT on the mol% of iPMA in polymer microgels.

### 9.4.3 pH sensitivity

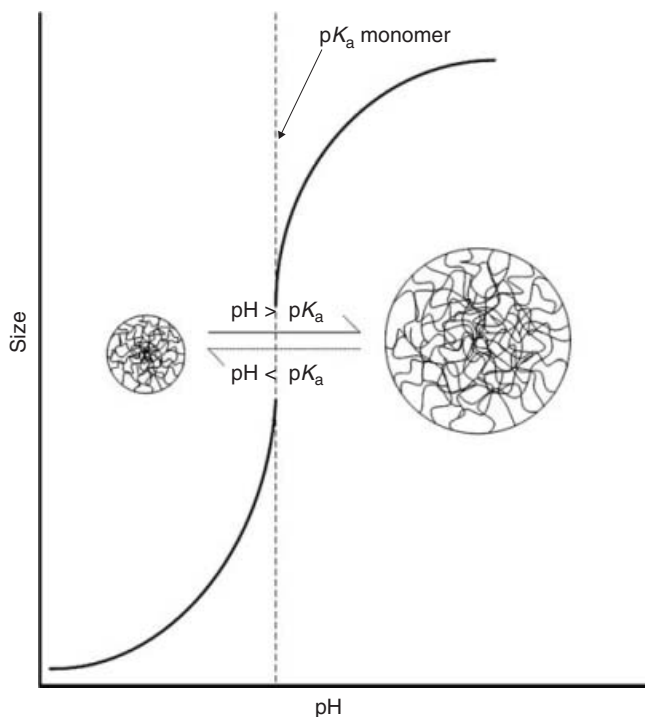
The mechanism controlling the swelling of microgel particles containing pH-responsive groups is governed by the internal osmotic pressure attributed to the mobile counter-ions contained within the particles, which balance the internal electrostatic repulsion [12]. The swelling of microgels is determined by the balance between the osmotic pressure inside the microgels and the osmotic pressure outside, as described by the following equation

$$\Pi_{\text{in}} + \Pi_{\text{el}} = \Pi_{\text{out}} \quad (9.2)$$

Where  $\Pi_{\text{in}}$  and  $\Pi_{\text{out}}$  are, respectively, the osmotic pressure of the mobile ions inside the microgels and bulk solution.  $\Pi_{\text{el}}$  is the elastic pressure of the polymeric network [73].

Microgel particles containing a weak acid or base (i.e. pH-dependent groups) are more complex. The ionisation of the sample is governed by the  $\text{p}K_{\text{a}}$ , or  $\text{p}K_{\text{b}}$  of the groups concerned, but these parameters are functions of the local charge group chemistry (a higher charge density suppresses ionisation) and background ionic strength (screens local electrostatic repulsion). Irrespective of the addition of any inert electrolyte, adjustment of pH itself inevitably leads to changes in background ionic strength [12].

Methacrylic acid polymers are well known for their pH sensitivity [74]. Incorporation of co-monomers containing acidic [75] or basic [76] functionalities into poly(NIPAM) microgels yields particles with pH driven swelling. For example, Snowden *et al.*, reported the



**Figure 9.10** The shrinking and swelling behaviour of a poly(NIPAM-AA) microgel.

preparation of poly(NIPAM) microgel particles containing AA groups. It was found that the hydrodynamic diameter (volume change) of the microgel particles increased with a corresponding rise in pH ( $pH > pK_a$ ). At a pH value above that of the  $pK_a$ , the polymer chains of the microgel become ionised, forcing the microgel to adopt a more extended conformation as a result of intramolecular charge repulsion. At a pH below the  $pK_a$  the microgel particles adopt a compact structure. Figure 9.10 represents the shrinking and swelling of a poly(NIPAM-AA) microgel.

#### 9.4.4 Swelling and de-swelling behaviour

The swelling and de-swelling mechanism of poly(NIPAM) microgels is generally attributed to the reversible formation and breakage of the hydrogen bonding between water molecules and hydrophilic amide groups within poly(NIPAM) polymer chains. Significant research has been carried out aiming at manipulating this delicate mechanism with a view to utilising it in a variety of potential applications.

The most important property for microgel particles is the extent of swelling. The extent of swelling is usually determined from changes in the hydrodynamic diameters measured using DLS. Microgels exhibit a larger swelling ratio at 4°C in contrast to that at 37°C.

Work discussing the theory of microgel swelling has been published by a number of groups. A model for describing the swelling of poly(NIPAM) networks has been employed by

Lele *et al.* [77]. They applied an extended lattice-fluid-hydrogen bonding theory (LFHB) to the swelling of poly(NIPAM) networks. Their working of microgel swelling data allowed the differentiation of hydrogen-bonded bound water and other bound water. A model used to predict the VPT for poly(NIPAM) microgels was devised by Prausnitz *et al.* based on Flory–Huggins theory [78] the result of which was close to experimentally derived data.

The swelling/de-swelling of microgel particles is controlled by the extent of cross-linking between the neighbouring polymer chains within the particles.

### 9.4.5 Effects of cross-linkers

The swelling/de-swelling behaviour of poly(NIPAM) microgels is dramatically influenced by cross-linker density. If the cross-linker density is high, the topological flexibility of the gel chains is restrained and the microgel particles have a relative compact conformation even in the swollen state. Consequently, the de-swelling ratio is decreased in the case of high cross-linker density [45]. However, the transition temperature remains almost constant, indicating that the thermodynamic process of the microgels does not change significantly.

Higher concentration of cross-linker will give rise to a faster conformational transition as the polymer chains are held closer together, thereby enabling a quicker collapse. Low cross-linker density results in microgels which display properties resembling high molecular weight polymers. Cross-linker density is usually employed somewhere between the two extremes, but is not evenly distributed throughout each microgel particle in a dispersion and is given as an average value per dispersion.

### 9.4.6 Osmotic de-swelling

Besides hydrogen bond formation, osmotic pressure also plays an important role in the swelling behaviour of some microgels. The pH-dependent hydrodynamic radius of a methacrylic acid ethyl acrylate-di-allyl phthalate microgel is studied as a function of the degree of neutralisation ( $\alpha$ ) of the carboxy groups in the gel network [73]. As  $\alpha$  increases, the hydrodynamic radius of the microgel increases continuously. This is because as the carboxyl groups are neutralised, the counter-ions trapped by the charged carboxylate groups enhance osmotic pressure within the microgel particles. Consequently the solvent molecules are driven into the particles by this increasing osmotic pressure and the microgel particles become swollen.

The first report of an osmotic de-swelling mechanism for microgel particles was by Sieglaff in 1963 for the polystyrene(microgel)/toluene/polystyrene(free polymer) system. Sieglaff suggested that an 'exclusion shell' for PS free polymer would be produced around the microgel particles; exclusion results when the polymer conformations required to penetrate the particle interior become entropically unfavourable [12]. Free polymer chains below a certain critical molecular weight may diffuse through the microgel particle pores into the microgel particle interior of a particle with a uniform pore size distribution. In such cases, the particle may swell. When the polymer chains are too large to penetrate the microgel particle interior, osmotic de-swelling results in collapse of the network. It is plausible that the pore size of the particles increases from the centre of the particle to the periphery.

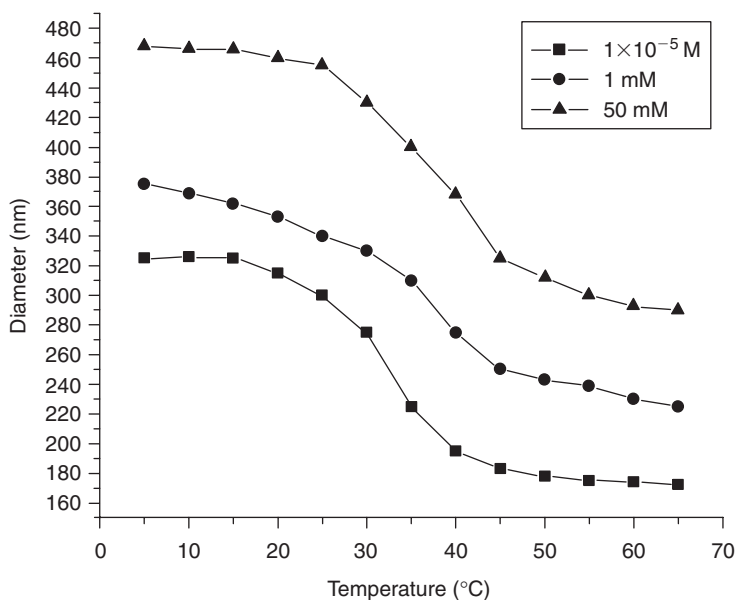
Polymer chains below a certain size may be able to penetrate the pores at the periphery. In that case, de-swelling of the particle core may occur to a greater extent than the periphery. Osmotic de-swelling is expected to increase any non-uniform pore size distribution already present within the particles.

Osmotic de-swelling of poly(acrylate) microgel particles in the presence of the sodium salt of PAA has been investigated by Kiefer *et al.* [79] using viscosity measurements. The results implied that added PAA did, indeed, cause de-swelling of the microgel particles. Excluded PAA may be expected to induce de-swelling of the particles due to the osmotic pressure of the mobile ions associated with the polyelectrolyte in addition to the contribution from excluded free polymer itself. However, low molecular weight PAA chains were believed to penetrate the microgel particle interior [12].

Similarly, osmotic pressure has been found to help to maintain the poly(NIPAM) microgels in the swollen state. The charged groups introduced by the initiators and co-monomers in the microgel network create an osmotic pressure that allows the solvent influx. Obviously, if electrolyte concentration of the bulk solvent increases, this kind of osmotic driven force will be weakened and the particle size would decrease, as proved by a study of the poly(NIPAM-co-AMPS) microgel [80] (Figure 9.11).

### 9.4.7 Colloid stability

Like other colloidal dispersions, the colloidal stability of microgels is determined by the balance between the van der Waals attractive forces ( $V_A$ ) and the repulsive forces ( $V_B$ ) applied on

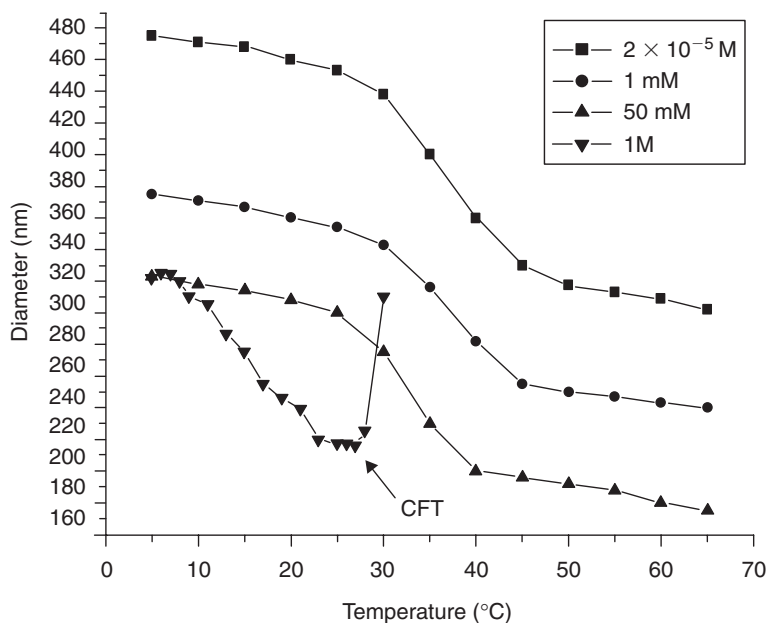


**Figure 9.11** Particle diameter by DLS as a function of temperature for different electrolyte concentrations (NaCl).

the particles. The net force  $V_T = V_A + V_B$ . The colloidal system is only stable if the  $V_A < V_B$  and the net force is negative. For microgel particles in the swollen state, most part of the particle volume is actually occupied by the solvent and consequently the Hamaker constant of the particles is similar to that of the solvent. This results in the van der Waals attraction between the microgel particles being weak and a stable dispersion. For poly(NIPAM) microgels, as charged groups are introduced by the initiators (such as  $K_2S_2O_8$ ), the dispersion keeps stable even when the solvent quality is poor in high temperature, due to electrostatic repulsion.

The stability of microgel particles in electrolyte is somewhat different to that of other model colloids. The importance of steric interactions to the stability of microgel dispersions is illustrated by the fact that poly(NIPAM) dispersions are stable in the presence of high electrolyte concentrations (such that electrostatic interactions are negligible) provided the dispersion temperature is below the VPTT. It has been shown that poly(NIPAM) microgel particles at 40°C flocculate at a sodium chloride concentration above 0.06 M [81]. These particles were found to re-disperse on cooling back to 25°C. The particles can remain dispersed at lower temperature as a result of the low van der Waals attraction forces when the particles are swollen in solution, therefore the particles can remain dispersion even though electrostatic repulsion is reduced. At 40°C the van der Waals forces increase as solvent has been expelled from inside the particles resulting in aggregation as the electrostatic repulsion is screened.

The situation becomes different when the electrostatic forces are screened by high concentration of electrolyte in the solution (1 M NaCl) [82]. When the temperature reaches the critical flocculation temperature (CFT), the microgel particles begin to aggregate, reflected by the sudden increase of the hydrodynamic diameter measured (Figure 9.12).



**Figure 9.12** Hydrodynamic diameter (by DLS) of poly(NIPAM-AMPS) microgel particles versus temperature for four electrolyte concentrations.

At high concentrations the interactions between microgel particles are determined by the dangling polymers on the surface of the microgel [83].

The most characteristic property of this flocculation is that it is reversible except for a critical quenching temperature range. When the temperature falls below the CFT, the steric repulsion force will dominate again and the microgel particles are re-dispersed.

A similar study has been carried out by Rasmusson and Vincent [84]. The flocculation behaviour of a poly(NIPAM) microgel is investigated as a function of ionic strength (introduced by NaCl in the solvent) and temperature. Three domains of the NaCl concentration have been established. The first when the NaCl concentration is lower than 25 mM, no CFT value could be determined therefore the microgel is stable at any temperature within the studied temperature range. The second NaCl concentration is range 25–100 mM. The CFT could be detected and it decreased strongly with increasing NaCl concentration. In this case, the electrostatic repulsion force is weakened. The third NaCl concentration domain is above 100 mM. The electrostatic repulsion force is completely screened out and the CFT decreases linearly with increasing NaCl concentration.

Chi Wu *et al.*, studied the flocculation of poly(*N*-vinylcaprolactam) microgels induced by different cations. At temperature higher than 32°C,  $\text{Ca}^{2+}$  and  $\text{Cu}^{2+}$  can induce inter-microgel aggregation [85]. The  $\text{Ca}^{2+}$  induced aggregation is essentially reversible in the heating and cooling cycle. Monovalent  $\text{Na}^+$  is not able to induce the inter-microgel aggregation. The complexation between  $\text{Hg}^{2+}$  and the carboxylic groups is so strong that the intra-microgel complexation becomes dominant.

### 9.4.8 Microgel structure

The structure of homopolymer microgels for example poly(NIPAM) has been shown to be non-uniform with respect to cross-linker distribution within the particles. In the reaction of NIPAM with BA by SFEP, BA has been shown to be consumed faster than NIPAM [6], inferring a particle consisting of a core with a higher cross-link density than the periphery of the particle. Recent SANS studies concerning microgels have reported that the particles have inhomogeneous structures with respect to cross-linker distribution which is shown to be concentrated in the core of the particle [86].

Co-monomers are usually introduced into NIPAM microgel in order to modify the physico-chemical behaviour of a microgel. A good example is the co-polymerisation with AA. AA residues bring higher charge density to the microgel particles. The electric static repulsion force generated by the charged groups has dramatic influence on the swelling behaviour of the microgels, causing higher VPTT and higher swelling ratio. Studies have been carried out to investigate the compositional structure of poly(NIPAM-AA) microgel particles with respect to the distribution of monomers within a particle. Some recent studies have overthrown the previous believe that the AA residues are uniformly distributed in the gel network. Xue *et al.* [87] found that the relative incorporation of NIPAM monomers in the growing chain is faster than that of AA monomers ( $r_{\text{NIPAM}} = 14 \pm 2$  and  $r_{\text{AA}} = 0.07 \pm 0.09$ ). This indicates a block polymer structure of the poly(NIPAM-AA) microgels.

Keiding *et al.* [88] developed an indirect method to evaluate the compositional distribution of AA residues in the poly(NIPAM-AA) microgel network. A two-phase model based on the Donnan concept has been developed to predict  $\text{pK}_a^{\text{app}}$  values as a function of  $\alpha$ . In the

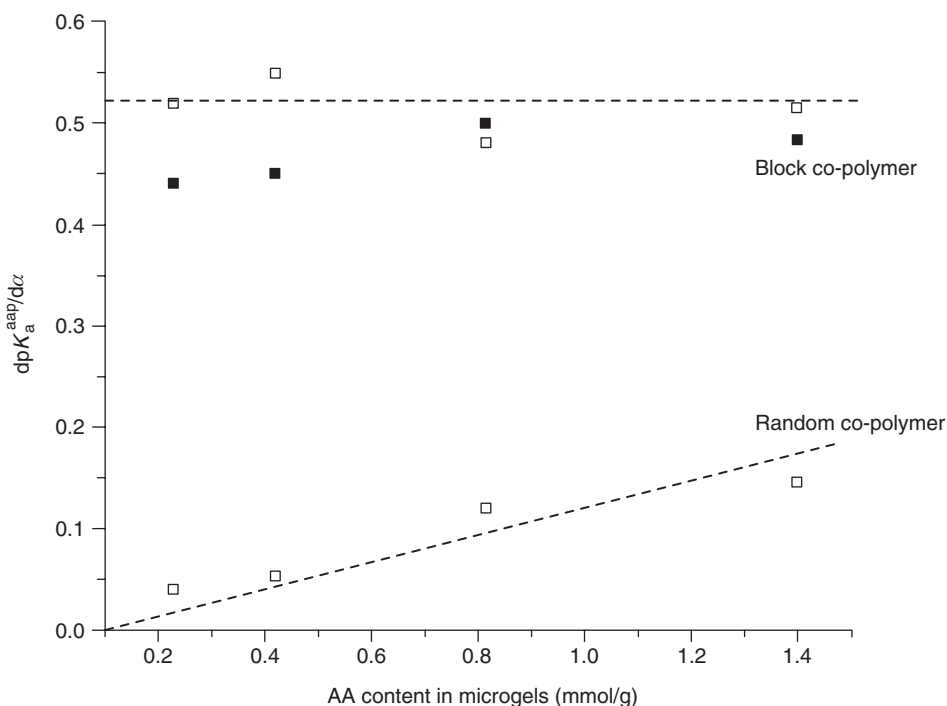


model, the microgel dispersions are separated into two phases: an AA phase that included all AA residues, and a bulk phase. For a random co-polymer, the AA phase consists of the whole gel network, and the volume of the AA phase corresponds to the hydrodynamic volume of the microgels. In this case, the  $\text{dp}K_a^{\text{app}}/\text{d}\alpha$  value should increase as the overall content of AA increase. For a block co-polymer, the AA phase consists of only the AA clusters while the bulk phase includes the rest of the gel network. In this case, the  $\text{dp}K_a^{\text{app}}/\text{d}\alpha$  value would keep constant as a function of the overall content of AA. The Potentiometric titrations are used to estimate the  $\text{p}K_a^{\text{app}}$  values.

Figure 9.13 shows that the compositional structure of the poly(NIPAM-AA) microgels is in consistence with a kind of block co-polymer rather than a uniform random co-polymer. Furthermore, they have suggested a core-shell structure with a hairy AA-rich shell.

### 9.4.9 Rheological properties

As with other physico-chemical properties of colloidal microgels the rheological behaviour of dispersions distinctly changes in response to environmental stimuli. At low temperatures the viscoelastic properties of poly(NIPAM) microgels change dramatically with temperature [89, 90]. At low temperatures poly(NIPAM) dispersions display elastic-type behaviour as



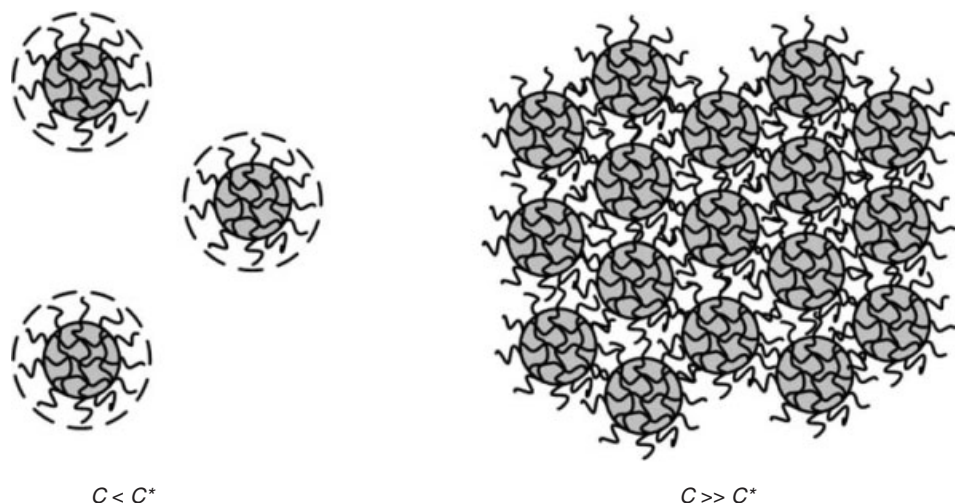
**Figure 9.13** Measured  $\text{dp}K_a^{\text{app}}/\text{d}\alpha$  values for poly(NIPAM-AA) (B0.6-A2.5), (B0.6-A5), (B0.6-A10), (B0.6-A15) and (B0.6-A20) (■). Predicted  $\text{dp}K_a^{\text{app}}/\text{d}\alpha$  values using a two-phase model based on the Donnan concept (□).

the particles are readily deformable below the VPTT. At temperatures above the VPTT the dispersion displays characteristics of any particulate dispersion.

The effect of cross-link density and conformation on the microstructure and rheology of a model pH-sensitive microgel system comprising of poly(methacrylic acid/ethyl acrylate) which swells when its carboxyl groups are neutralised [73] has been investigated. In the swollen state a pronounced increase in the viscosity and shear thinning of the system is observed. The authors were able to relate the physico-chemical characteristics of the microgels with their bulk rheological behaviour.

When investigating the rheology of dispersions as a function of concentration it has been found that the rheological behaviour of microgel particles is equivalent to that of hard particles with a thin, soft shell. Dilute microgel dispersions exhibit Newtonian flowing properties, whereas concentrated dispersions are highly shear thinning. The water-swellaable microgel of poly(dimethylacrylamide/2-acrylamide-2-methyl-1-propanesulfonic acid) cross-linked with BA been synthesised and its rheological properties investigated [91]. The microgels behave distinctively differently at low concentrations and high concentrations. At low concentrations, the microgel dispersions behave like Newtonian fluid, showing no change of viscosity in response to the shear rate. At high concentrations, however, not only the overall apparent viscosity increases, but the viscosity becomes dependent on the shear rate, showing a shear-thinning property.

The microgel dispersions display a shear-thinning characteristic at high concentrations, a behaviour similar to that observed for bulk gels. In fact a bulk-gel-like structure is suggested for microgels at high concentrations [91]. At concentrations higher then the overlap concentration ( $C^*$ ), the microgel particles are packed together such that the tangled polymer chains on the surface of the particles would create a bulk-gel-like continuous network (Figure 9.14).



**Figure 9.14** A schematic illustration of the microgel aqueous dispersion in dilute and semi-dilute regime. In the figure,  $C$  and  $C^*$  represent the concentration of the microgel and the overlapped concentration of the microgel.

Cloitre *et al.* [92] reported similar behaviour for a polyelectrolyte microgel. In dilute suspensions, the polyelectrolyte microgel behaves like a soft Brownian fluid, whilst above close-packing they form pastes which share many features (elasticity, yielding behaviour, and aging) common to other pastes and slurries. These features even make this concentrated polyelectrolyte microgel a good model in understanding the properties of colloidal pastes.

#### 9.4.10 Electrical properties

The electrical properties of microgels, brought about by the charges introduced by the initiator, are an interesting aspect of dispersion behaviour. When in the swollen conformation the electrophoretic mobility of microgel particles is close to zero, which increases by an order of magnitude once the system has undergone the VPT. This is due to the dramatic change in particle surface charge density. A study investigating the electrophoretic mobility of ionic microgels based on 2-VP [93] found that in the swollen state microgels behave as spherical polyelectrolytes, whereas in the collapsed state they behave as hard spheres.

#### 9.4.11 Drug delivery vehicles

One potentially exciting area in which there is currently much research activity taking place is in the field of microgels as potential drug delivery vehicles. Conventional delivery systems suffer from limitations of minimal synchronisation between the required time for therapeutically effective drug plasma concentrations and the actual release profile exhibited by the dosage form. Drug delivery vehicle design is normally based on the physico-chemical and pharmacokinetic properties of the drug of interest. Current investigations into drug delivery system design are focussing on the controlled release of rapidly metabolised drugs and the protection of sensitive drugs or proteins. Both of these requirements could come from swelling controlled release systems, such as microgels. The ability of microgels to undergo rapid and dramatic conformational changes from an effectively closed to an open structure make them, at least in principle, ideal drug delivery vehicles.

Microgels are being studied with the aim of developing oral drug delivery devices [94, 95]. Ternary co-polymer microgels of poly(NIPAM/butyl methacrylate/AA) have been investigated with respect to their potential application for the modulated delivery of insulin [96] and thereby may offer the possibility for an oral delivery route. The butyl methacrylate component fulfils two roles within the microgel structure. Firstly it confers improved mechanical properties onto the microgel; secondly the butyl methacrylate moiety facilitates an enhanced absorption of insulin as a result of the hydrophobic butyl component of the side chains. It was found that, at low pH (pH 2) below the  $pK_a$  of the AA, where the microgel adopts a compact conformation (closed structure), the rate of insulin release was very low. Conversely by raising the pH (pH 7.4) above the  $pK_a$  of the AA, the microgel changes conformation to adopt a more open structure as the intramolecular charge repulsion between the acrylate groups causes a conformational expansion. The majority of the remaining encapsulated in the particle insulin was released at this pH. This experiment mimicked the delivery of insulin via a microgel, passing through the stomach (which has a low pH), illustrating the potential of a microgel as a protective barrier for the insulin. On moving

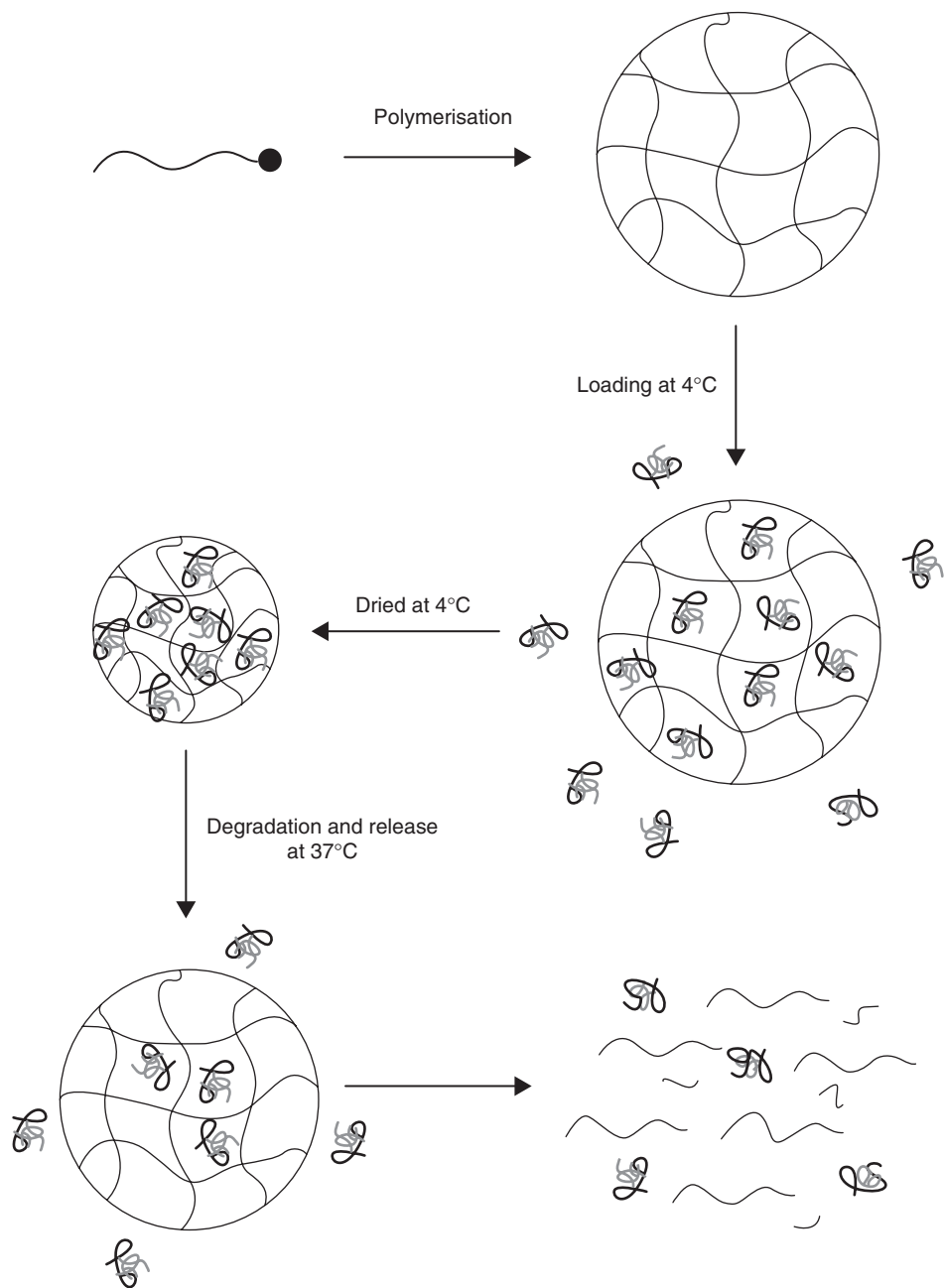
out of the stomach along the gastro-intestinal tract the pH increases which allows the cage to open and deliver the insulin into a much less harsh environment.

Microgels synthesised using vinylpyrrolidone co-polymerised with AA have been investigated by Sahoo *et al.* as an oral drug delivery device [97]. The microgel particles under investigation were loaded with a marker compound, FITC-dextran, and the release of this compound was monitored as function of pH and temperature. The compound release was found to be slow in an acid solution, when the structure is collapsed, but rapidly increased with increasing pH. The release was also found to be temperature dependent. At 4°C around 18% of the FITC-dextran was released whereas approximately 50% was released when the dispersion was heated (37°C).

*Cis*-platin is a commonly used chemotherapeutic agent for the treatment of various cancers. In order to develop a platform for the release of this compound to the local environment of a tumour (to alleviate problems associated with the high doses currently employed) poly(AA/methyl methacrylate) microgels have been synthesised [98]. The carboxylate containing monomers were employed to complex with the *cis*-platin. The absorbance of *cis*-platin into and release from these microgels has been determined. An interesting aspect of this research were that the *cis*-platin released from the microgels had only slightly reduced activity when compared to freshly prepared *cis*-platin. The low *in vivo* acute toxicity ( $LD_{50} > 170 \text{ mg/kg}$ ) of this systems infers that hydrogel particulate systems should be studied further for such applications.

Although much progress has been made in the field of pharmaceuticals, protein based delivery is still quite challenging. In order to avoid the factors which commonly lead to protein denaturation, such as organic solvents and high temperatures a novel biodegradable microgel was prepared by a novel inverse suspension polymerisation reaction [99, 100]. The VPTT was between 4°C (around the refrigerator temperature) and 37°C (human body temperature). Proteins were encapsulated into the network of the microgels at 4°C, which led to highly swollen microgels having the capacity for relatively high loading and retaining the possibility of preserving spatial structures of proteins during encapsulation. At 37°C the protein was entrapped into a relatively less swollen microgel, which might avoid a burst release. The complete release of the encapsulated protein may be achieved by degradation of the network. The microgel and associated post-fabrication encapsulation is schematically presented in Figure 9.15. Such a system and the post-fabrication encapsulation technique based upon this kind of hydrogel microparticles provides a novel carrier for protein drugs and a unique way for controlling the loading and release of protein drugs [100].

The use of colloidal microgels as potential transdermal drug delivery systems has recently been reported in the literature [101, 102] and it was reported that microgels have potential in drug delivery to the skin. They may be of particular importance where the skin barrier is compromised for example if the skin is in a diseased state, or in wound management). In these situations controlled delivery to the skin of actives can provide therapeutic levels where required and minimise systemic uptake. Microgels could be used at higher temperatures and release more material as may be anticipated within wound tissue. They appear to be pH insensitive in the release of the compounds and therefore any pH effects in the wound would be negligible [101]. Another problem in transdermal delivery is skin toxicity. Drug molecules that are applied to skin must be relatively innocuous, neither creating irritancy nor allergenicity. In some circumstances using a larger patch area can alleviate the problem. Because of this issue and taking into consideration one of the possible practical



**Figure 9.15** Schematic representation of a post-fabrication encapsulation strategy of protein drugs based upon a smart, biodegradable microgel. Microgels were obtained from cross-linking pre-designed macromers. After microgel preparation, drug loading was performed by soaking an aqueous solution of proteins with microgels at 4°C (<VPTT). The microgel particles collapsed after drying and the proteins became entrapped in the microgel network. When transferred to phosphate buffer solution at 37°C the release of protein was reduced (in comparison to at 4°C) which can be attributed to microgel shrinkage. The release proceeded as a result of the hydrolysis of the microgels. All proteins contained within the network were eventually released due to complete biodegradation of the polymeric network.

applications of 'smart materials' in wound treatment [103, 104], the idea of using pH/temperature sensitive microgels as transdermal drug delivery systems was considered.

The synthesis and properties of microgels based on NIPAM and butyl acrylate, in the presence and absence of ibuprofen (IBU), methyl paraben (MP) and propyl paraben (PP) were investigated. IBU is chosen as a model drug [102]. It is speculated that the microgel appearance is similar to a core-shell microgel, having in the core the complex IBU- or MP- or PP-butyl acrylate and in the shell poly(NIPAM). Permeation across a model silicone membrane and human skin was investigated over a range of temperatures (292–313 K). The transport rate of IBU and, PP from these poly(NIPAM) microgels is significantly reduced by two and one orders of magnitude, respectively, compared with the transport rate from saturated solutions. Such a reduction in flux was not however observed for MP. The authors concluded that high log *P* drugs that is those having the lowest water solubility tend to associate with the microgel much more strongly than their more water soluble counterparts. Under these circumstances it would appear that colloidal microgels may behave as 'reservoir sinks' and facilitate a slow zero order release of the entrapped material.

#### **9.4.12 Other current areas of applications**

There are a variety of other possible applications for microgel particles. Some of the applications have already been achieved (e.g. rheological control additives); whereas many more are yet to be realised [12].

The main applications involving microgel particles have been in the surface coatings industry [1, 12, 13]. Microgel particle dispersions are shear thinning and provide rheological control for automotive surface coatings. The particles also have good film forming properties and favour the alignment of added metallic flakes parallel to the substrate surface. The original motive for employing microgel particles in surface coatings arose from US EPA regulations that required a decrease in the volatile component of surface coating formulations. This was achieved by increasing the total solids content by decreasing the molecular weight of the linear polymer, however, this led to an unacceptably low viscosity. Microgel particles were added in order to increase the dispersion viscosity. The microgel particles had the added effect of imparting a yield stress to the dispersion. Surface coating formulations often contain residual linear polymer which may affect microgel particle swelling. It has shown that dispersion of microgel particles in the presence of added polymer results in partial de-swelling of the particles by osmotic de-swelling.

Microgel systems also show promise in the printing industry. Microgel particles may be functionalised to yield photo-cross-linkable particles. The high surface area and good surface-coating characteristics have allowed functionalised microgel particles to be used as printing offset plates with impressive results [12].

Water-borne polymers are widely used in personal care products and cosmetics as viscosity thickeners. A viscosity thickener is an extremely important raw material for the cosmetic industry because it brings about texture change. An issue inherent in the use of common linear polymers as thickeners is that they create a 'sticky feeling.' This feature is most likely to be related to the 'spinnability' of the polymer solution. One of the most suitable alternative candidates for cosmetic thickeners is microgels. Spinnability is probably related to the entanglement of polymer chains and therefore, because of their cross-linked structure, microgels are

regarded as having no 'spinnability,' as there are so few free chain lengths to entangle. Agar, a gel-forming polysaccharide extracted from a kind of seaweed, has been applied as a microgel thickener for cosmetics [7]. The result of these studies was shown that the thickening effect and texture correlated with the size of the microgel particles. The smaller the microgel particle, the more effective the particle is as a thickener, and hence the better the texture. Control of microgel particle size is therefore an important issue for the development of cosmetic thickeners. As personal care products and cosmetics are required to be stable over a wide pH range, it is necessary to thicken such products with a suitable material that will remain functional in a variety of conditions.

Another area for application of microgel particles is in water purification. Poly(NIPAM-AA) microgel particles take up heavy metal ions. However, the efficiency of uptake is low due to the restricted proportions of AA that can be used during preparation. Improvements are likely when microgel particles containing high carboxyl contents are prepared. Moreover, it should be possible to produce chelating monomers which will specifically bind target metal ions.

The synthesis of hybrid materials by encapsulation of an inorganic material or a liquid in a polymer matrix opens new possibilities in the fabrication of solid particles for materials science. Such composite particles offer potential advantages in applications such as cosmetics, inks and paints coming from the improved compatibility between the filler and the binder. Polymer shells encapsulating inorganic particles are also of great interest in pharmaceutical and biotechnological industries for producing drug release products. However, recent studies have underlined the major difficulty to encapsulate inorganic particles homogeneously, especially in the case of magnetic particles in polymer microgels.

Aqueous magnetic fluids are colloidal dispersions of magnetic nanoparticles in water, exhibiting a giant paramagnetic behaviour. They can be used in biosciences, namely as contrast agents for magnetic resonance imaging (MRI), for magnetic guidance of drugs or radioisotopes and for cell sorting processes [54].

Microgels have also been reported as valuable materials to be used in conjunction with molecular imprinting technology. Their main advantage is their solubility and therefore possibility of using them for a variety of different applications in which insoluble counterparts cannot be applied. It was shown that catalytic microgels useful for carbonate hydrolysis were obtained by high dilution radical polymerisation using a combination of functional monomers mimicking the mechanism of action previously seen with enzymes and catalytic antibodies [105]. A number of different preparations were obtained, using percentages of cross-linker ranging from 70–90%. Full physico-chemical characterisation has shown the resultant particles to be microgels. Moreover studies on the catalytic activity of these preparations seem to indicate that the lowest cross-linking percentage, that is 70%, leads to the best catalytic activity. This is the first step towards our long-term goal of developing efficient catalytic systems and further investigations using this approach are currently in progress [105].

## **9.5 Conclusions**

Colloidal microgels have attracted considerable attention over the past 10–15 years and many attempts have been made to try to better understand the correlation between their structure and resultant properties. As microgels can be prepared in a variety of different

ways and may contain a wide variety of monomer types there are many possibilities of developing novel architectures and morphologies for these interesting materials. In recent years the diverse application of microgels in the development of high value products, such as cosmetics and specialist paints and in the biomedical field for applications including controlled release, transdermal drug delivery and protein encapsulation, has increased enormously. With a clearer understanding of their structure and physico-chemical properties it is likely that the range of applications will continue to grow further.

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## Chapter 10

# Industrial Water Soluble Polymers in Packaging

*Radek Messias de Bragança and Paul A. Fowler*

### 10.1 Introduction

Industrial water soluble polymers (IWSPs) represent just a small fraction of polymers used in packaging (mainly as polyvinyl alcohol (PVOH), ethylene-vinyl alcohol copolymer (EVOH), and ethylene-vinyl acetate copolymer (EVA)), but depending on additional research, two factors may lead to a growth of their relative importance: the need to ensure (1) renewability and (2) biodegradability.

The aim of this chapter is to describe why IWSPs may be key to answering these two challenges, to provide a succinct description of the most important polymers and IWSPs used in packaging, and to analyse the critical properties of materials used in packaging, including processes (and products), and to try to indicate trends in research and development.

### 10.2 Present-day challenges to IWSPs for packaging

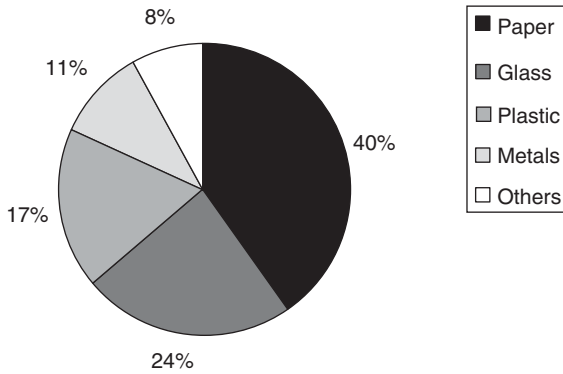
#### ***10.2.1 Renewability paradigm, or predicted exhaustion of world petroleum reserves and global warming challenge***

In 2003, world plastic production amounted to approximately 197 millions tonnes. A significant quantity (25%) of this total was used in the packaging sector, and around 40% of the European packaging market counted for plastics (see Figure 10.1).

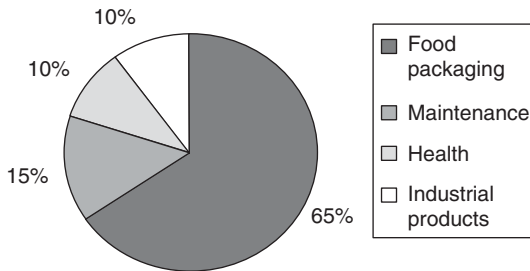
End uses of plastic packaging show the predominance of food packaging (65%), with the balance containing maintenance and cleaning products and industrial products (Figure 10.2).

Despite the huge variety of polymers available, the most important types of polymers presently used in packaging are from five major families: polyethylene (PE), polypropylene (PP), polyethylene terephthalate (PE), polystyrene (PS), and polyvinyl chloride (PVC) (Figure 10.3).

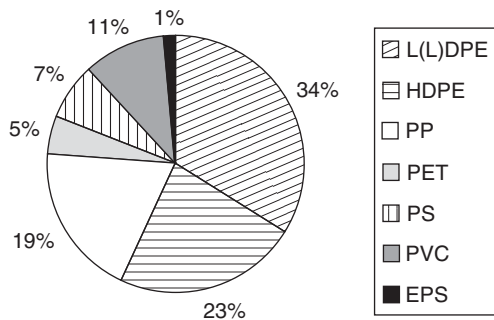
All these families arise from petrochemical resources and this raises the question of the security of supply of fossil reserves to ensure the sustainability of plastic packaging. World reserves of oil are estimated at roughly  $1-1.5 \times 10^7$  tonnes, more or less 40 years of consumption at the present rate. However, these values do not allow an easy correlation to the rate of petrochemical resource extraction and depletion. Many schools of thought have



**Figure 10.1** Materials used in packaging in the EU, 2004.



**Figure 10.2** Uses of plastic packaging in the EU, 2004.



**Figure 10.3** Packaging consumption as a function of type of polymers.

emerged to try to predict this rate, some optimistic, others pessimistic with a range of opinions in between.

The optimist school, based mainly at the Massachusetts Institute of Technology, estimates that possible production/depletion is a function of the technical progress which

would allow a better exploitation of existing reserves (by, e.g. reduction of drilling costs, improvement of oil recovery, and better geological estimates). Such technical progress is exemplified by oil extraction in Venezuela where, in the 1980s, extraction of heavy crude was considered feasible only when the price per barrel reached USD50. However, technological advances have reduced this threshold to USD15 by 2004 [1].

Conversely, the most pessimistic analysis is presented by the Association for the Study of Peak Oil and Gas, which suggests that the global production of oil had already peaked in the spring of 2004 [2]. Furthermore, in March 2005, the Algerian minister for energy and mines stated that OPEC had reached its oil production limit [3], while in September 2005, British Gas raised its prices blaming falling oil reserves [4].

An intermediate vision is presented by the United States Geological Survey (USGS) which estimates that there are enough petroleum reserves to continue current production rates for 50–100 years. In 2000, a USGS study of worldwide oil reserves predicted a possible peak in oil production around the year 2037 [5]. The US Department of Energy predicts that global oil production will peak somewhere between 2020 and 2050, but that the output is likely to increase at a substantially slower rate after 2020 [6]. Price speculation is likely to increase petrochemical prices before peak oil production is reached.

Another reason to focus on the sustainability of packaging polymers arises from the fact that consumption and subsequent disposal of petrochemical-based resources leads to increased carbon dioxide emissions [7], with concomitant effects on global warming. Thus, continued increase in petrochemical production requires an increased exploitation of non-conventional sources, suggesting market opportunities for new, renewables-based IWSPs.

### 10.2.2 *Need to ensure biodegradability in packaging materials*

The current petrochemical-based packaging polymers (PE, PP, PS, PET, and PVC) have a useful life for a very limited period (extremely small if the lifetime of the material is considered) and are major causes of pollution [8].<sup>1</sup> Different approaches have been adopted to tackle the problem such as:

- (1) The possible recycling of the polymer. A classic example is the recycling of HDPE milk bottles that are reused to produce laminate for bottling liquid detergents. This approach has limitations as the properties of the recycled materials are reduced and require the addition of virgin materials to increase the performance to an acceptable standard. The repeated recycling of a plastic leads to degradation of its thermo-mechanical properties and it is, therefore, accepted that only a small fraction of polymers can be recycled.
- (2) Reconversion of plastics into new raw materials for the petrochemical industry. This approach, called 'back to petrol', is still in its infancy with some pilot plants established for depolymerisation by hydrolysis or thermal cracking.

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<sup>1</sup> A recent report (Van Franeker *et al.*, 2004) reported that 98% of Northern Fulmars from the North Sea had one or more pieces of plastic in the stomach (average 32 pieces or 0.34 g per bird).

- (3) Recovery of the energy content of the polymer. The success of this strategy relies on achieving a balance between the cost of the collection of the polymer materials and the value of the energy recovered.
- (4) Use polymers that would degrade themselves once their useful life is passed.

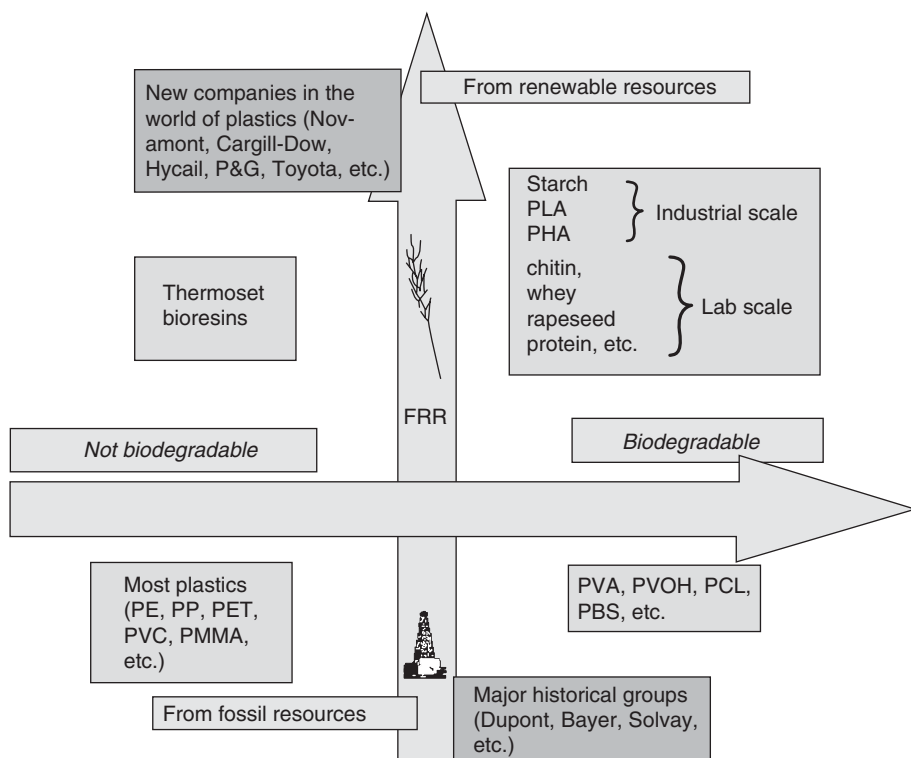
It is expected that all four approaches would be complementary, but the last one provides market opportunities for IWSPs, either from natural or petrochemical sources, which are biodegradable.

### 10.3 Survey of IWSPs used in packaging

Figure 10.4 places the major groups of polymers used in packaging applications along two scales: (1) their sources and whether they are naturally or synthetically derived and (2) their degradability and whether or not they are biodegradable.

Five major polymer families are important in terms of mass production. These are the thermoplastics that include PE, PP, PVC, PS, and PET. These appear in the bottom left quarter of Figure 10.4, which corresponds to 'not biodegradable' polymers 'from fossil resources'.

Into the bottom right quarter of Figure 10.4 fall EVOH, EVA, polyvinyl acetate (PVA), and water soluble polymers such as polycaprolactone (PCL) which are synthetic (petrochemical



**Figure 10.4** Polymers used in packaging.

based) that have, in addition with other properties discussed later, the advantage of being biodegradable. These have been, in general, developed by major chemical groups, with known skills in polymer processing.

The top left quarter of Figure 10.4 comprises thermosetting bio-derived resins that typically do not feature in packaging applications and so will not be discussed further. Most interestingly, in the context of biodegradable, renewable materials is the top right quarter that comprises polylactic acid (PLA), starch, polyhydroxy butyrate, whey protein, and so on. Each of the petrochemical and non-petrochemical derived IWSPs are discussed in turn below.

### 10.3.1 *Synthetic IWSPs*

#### 10.3.1.1 *Polyvinyl alcohol*

PVOH was the first fossil-based industrial water soluble thermoplastic polymer used in packaging. It is a resin with user-controllable solubility in water and, depending on the formulation, materials can be designed to dissolve within a preset temperature range [9]. After several minutes' immersion at a designated temperature, the polymer will dissolve to leave a solution of PVOH with small amount of glycerol (or other polyol). Once in contact with micro-organisms, biodegradation to carbon dioxide and water takes place within about 30 days [10].

Formulated PVOH films have good clarity, good gas barrier properties ( $0.0008\text{--}0.06\text{ ml/m}^2/\mu\text{m}$  depending of the formulation), high mechanical strength (of around  $50\text{--}60\text{ MN/m}^2$ , which is about three times that of low density polyethylene (LDPE)), and high tear strength and puncture resistance (around  $1040\text{--}1070\text{ N/mm}$ , when dry, two and half times that of standard polyethylene LDPE film) and are stable under moderate but not high humidity conditions.

Standard formulations comprise resins in the range of 65–80%; plasticiser 0–20%; water 2–20%, and 0–20% of other polymers useful as modifying agents in the film. Suitable plasticisers are glycerol and other non-toxic polyols. Gellan and konjac gums are used as additives and serve to prevent the PVOH film from dissolving in hot water and during steam processing [11].

However, the processing of these films requires modifications to standard PE handling machinery. Generally, film output is limited, the film stiffens as it cools unless allowed curing time in a warm environment, careful handling and storage are necessary, implying the need to employ highly skilled operators to extrude and wind films [12].

The material is currently used to manufacture laundry bags for hospitals, soluble bags for the agriculture/horticulture industry, compostable garden waste bags, washable labels (these can be washed away with hot water during recycling operations), and liquid detergent packaging.

#### 10.3.1.2 *Ethylene-vinyl alcohol copolymer*

EVOHs were first commercialised in Japan in the early 1970s to overcome the moisture sensitivity of the PVOH films. These copolymers are a family of random semicrystalline materials with excellent barrier properties to gases and hydrocarbons and with outstanding

chemical resistance [13]. EVOH copolymers are commonly produced via a saponification reaction of a parent ethylene-co-vinyl acetate copolymer, whereby the acetoxy group is converted into a secondary alcohol. These materials are primarily used in food packaging and pipe applications where stringent criteria in terms of chemical resistance and in gas, water, aroma, and hydrocarbon permeation must be met. In particular, the copolymers with low contents of ethylene (below 38 mol.% ethylene) have outstanding barrier properties, under dry conditions, compared to other polymeric materials.

EVOH films provide an excellent oxygen barrier in dry applications, but do not provide a good moisture barrier. In addition, the oxygen barrier diminishes at elevated relative humidity levels. Co-extruded biaxially oriented films containing EVOH have use in processed meat, cheese, and some dry food packaging applications.

The shrinkage of EVOH films is typically in the range of 15–20% at temperatures below 85°C. Higher shrinkage rates are possible at higher temperatures, but these elevated temperatures can cause discolouration and other undesirable side effects to meat being packaged. The EVOH commonly used in double bubble films is a 44 mol.% ethylene. Recent findings have shown that the oxygen barrier of EVOH can increase as much as 20% during the orientation and heating processes encountered in a biaxial orientation process.

EVOH is co-processed with other polymers (see Table 10.1) to improve strength, crack resistance, and heat sealability. Some end-use applications and modes of processing are also shown in Table 10.1. Additionally, recent research suggests the possibility to use nanolayered coatings to improve mechanical properties [14], and the use of multilayered EVOH–PE films in the manufacture of bags for blood/blood substitutes, and intravenous (IV) enteral feeding and drug-delivery systems. These films have critical oxygen barrier parameters and present reduced risk of contamination by plasticiser migration over the presently used PVC bags [15, 16].

### 10.3.1.3 Ethylene-vinyl acetate copolymer

EVAs are long chains of ethylene hydrocarbons with acetate groups randomly distributed throughout the chains. Ethylene is copolymerised with the vinyl acetate to form ethylene vinyl acetate copolymer.

Ethylene vinyl acetate is processed by extrusion. The extruded film may be used to produce blown film, coated film, tubing, profiles, and extrusion blow moulded products. EVA should be kept under 230°C or it will begin to degrade.

**Table 10.1** EVOH laminates, fabrication processes, and applications [17]

Fabrication process	Application	Structure
Cast extrusion	Processed meat, cheese, snacks, bakery	PP/nylon/EVOH/nylon/LDPE
Blown extrusion	Processed meat, red meat, pouches	Nylon/EVOH/nylon/LDPE
Lamination	Coffee, condiments, lidstock	OPET/EVOH/PET/PP
Co-extrusion coating	Juice, bakery, laundry products	OPP/LDPE/EVOH/LDPE/EVA
Thermoforming	Vegetable, fruit sauces	PS/EVOH/LDPE
Co-extrusion blow moulding	Ketchup, sauces, salad dressing, agricultural chemicals	PET/EVOH/PET/EVOH/PET
Profile extrusion	Cosmetics, toothpaste	LDPE/EVOH/LDPE



Blowing is the most popular method of producing film. It is produced by blowing a bubble out of the heated monomer. The bubble is then cooled creating a film of the polymer. EVA film is used for packaging because it has low sealing temperatures allowing fast production cycles and because it complies with FDA regulations for materials that come into contact with food [18].

EVAs are used to extrusion coat many substrates including nylon, polyester, cellophane, and polypropylene films. EVAs are excellent heat sealers, have good hot tack strength, and adhere well to a variety of substrates. The tackiness of EVA copolymers can cause problems in extrusion coating but using dusting powders on the film and additives in the polymer can help the process run smoothly [19].

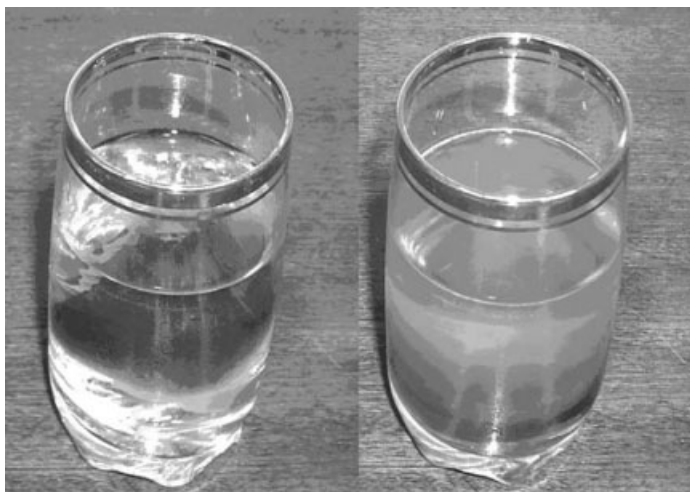
Casting is the second most popular method of producing EVA film. Dual chill roll systems are used to roll the EVA copolymer into sheets of thin film. Additives are sometimes needed to alleviate problems with blocking and poor chill roll release. Sheet extrusion is very similar to cast film extrusion except the EVA copolymer product is much thicker. Sheet extrusion usually uses three or four chill rolls stacked one on top of the other instead of the two generally used for casting.

Extrusion blow moulding is typically used to produce large, hollow parts such as bottles. For EVA, extrusion blow moulding is generally preferred to injection blow moulding. Some properties of EVA can be controlled by adjusting the content of vinyl acetate in the copolymer. For instance, higher vinyl acetate content yields a higher permeability to oxygen, nitrogen, carbon dioxide, and moisture vapour. But EVA copolymers are all flexible with a high flex life, have good film clarity, and are resistant to ozone. Their polar functionality promotes adhesion to polar substrates (paper, polyester, wood, and leather) and more readily accepts inks. Low crystallinity gives it a low melting point and excellent low temperature toughness.

#### 10.3.1.4 *Polyethylene oxide blends and copolymers*

Polyethylene oxide (PEO) is traditionally used as a lubricant additive but Dow has introduced a polymer grade by copolymerisation with PVOH. Low molecular weight PEO resins have desirable melt viscosities and melt pressure properties for melt processing but have limited solid state properties when melt processed into structural articles, such as films, and high molecular weight PEO has limited processability. Unmodified PEO films have inherently low strength, but have relatively greater ductility than PVOH films. PVOH resins have relatively high strength compared to PEO resins. These are both water soluble and thermoplastic, but have low ductility and are inherently brittle, and as reported, need to be formulated with plasticisers. A solution has been the production of completely water soluble grafted-PEO with PVOH that do not require plasticisers in order to be thermoplastically processed. Blends have been shown to be non-miscible, but copolymers have greater ductility than PVOH films, and greater tensile strength than the grafted-PEO films [20].

Another technique used to improve the properties of PEO has been cross-linking with polyurethane chain extension, which is used currently to produce water soluble packaging (sachets, capsules, bags) [21]. Such films can, for example, have improved solubility in cold water compared to conventional PVA films; also unlike PVA films, they have good mechanical properties and good heat seal characteristics without the need for added plasticisers. Figure 10.5 shows that a detergent packaging introduced into cold water dissolves after just 5 min at room temperature.



**Figure 10.5** Solubility of an EVOH-copolymer structure.

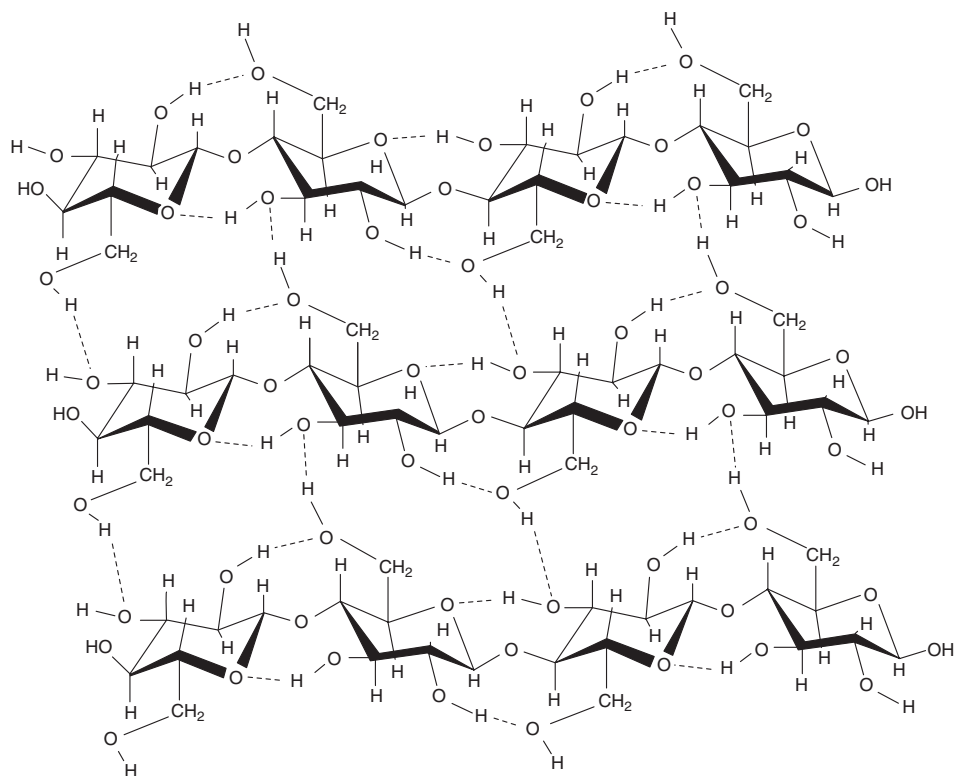
### 10.3.2 Naturally derived IWSPs

#### 10.3.2.1 Cellulose

Cellulose is a linear homopolymer of glucosic residues comprising  $\beta$ -(1 $\rightarrow$ 4) bonds as shown in Figure 10.6.

Cellulose-based films have an extensive history and technology. A common characteristic is that such films are produced by chemical, mechanical, or combinations of chemical and mechanical processing of structural plant matter to provide a sheet-like matrix. This matrix contains dispersed or partially disintegrated cell walls and may contain numerous additives to improve processing or end-use function. The most prevalent commercial form is paper and paper-related constructs such as cardboard or corrugated cardboard. This chapter will concern itself no further with paper.

Cellulose may be used to make flexible and transparent films. The best-known example is cellophane, a regenerated cellulose, obtained by extrusion of an alkaline dispersion of xanthate of cellulose in an acid bath. A film is obtained after treatment with a plasticiser (glycerol) and drying. Esters and ethers of cellulose can also be obtained. Some, like cellulose acetate, propionate, and butyrate are thermoplastic products of commercial importance. The anionic cellulose ether, carboxymethyl cellulose (CMC), being water soluble and compatible with other (bio-)molecules, has excellent film forming properties. CMC films are capable of reducing oil pick-up in deep-fat-fried foods. CMC with a degree of substitution 0.7 is usually used in such applications. From an environmental point of view, these processes have been criticised because they are energy intensive, and create large amounts of carbon dioxide emissions [22]. In food packaging applications, cellulose polymers are also used to produce edible films. Commercially available composite coating formulations-based on CMC contain sucrose fatty acid ester, the sodium salt of CMC, and emulsifier. Such formulations are used for shelf-life extension of banana and other fruits. In trials,



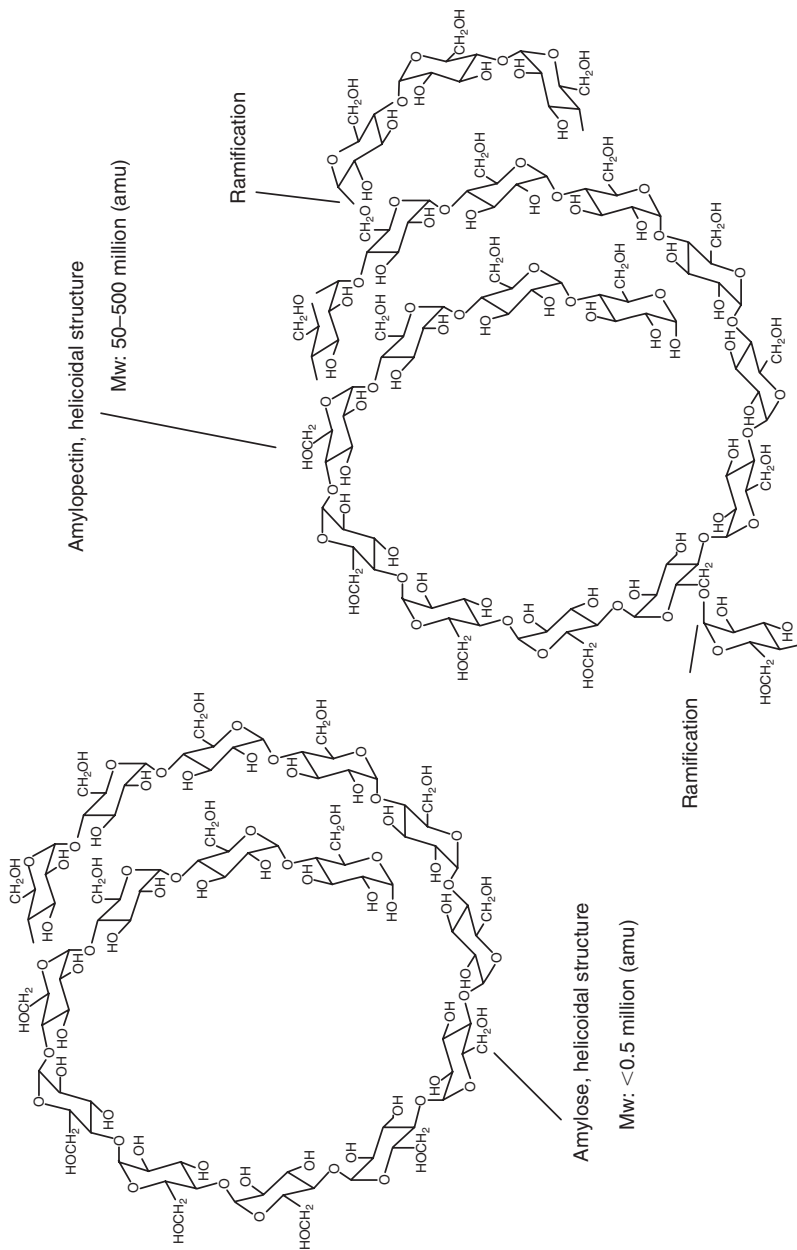
**Figure 10.6** Cellulose structure.

coated banana showed decreased oxygen levels and rise in ethylene production which delayed chlorophyll loss. Mangos and tomatoes, when similarly treated showed delayed ripening with an extended shelf-life [23].

### 10.3.2.2 Starch

Chemically, starch is a combination of two polymeric polysaccharides called amylose and amylopectin in which glucose monomers are joined to one another head-to-tail by  $\alpha$ -(1 $\rightarrow$ 4) linkages. Linearly combined units constitute amylose, while branched units constitute the amylopectin (see Figure 10.7). Structurally, the starch forms clusters of linked linear polymers, where the  $\alpha$ -(1 $\rightarrow$ 4) linked chains form columns of glucose units which branch regularly at the  $\alpha$ -(1 $\rightarrow$ 6) links (Figure 10.7).

The relative content of amylose and amylopectin varies between species, and between different cultivars of the same species. For example, high-amylose pea starch comprises about 75% amylose whilst waxy corn starch contains more than 99% amylopectin.

**Figure 10.7** Starch structure.

Research on starch-based plastics began in the 1970s and continues today in various laboratories worldwide. In the 1980s, it was found that thermoplastic starch polymers could be obtained by a process called destructureation, in which starch is submitted to a treatment at high temperature (and/or high pressure) in the presence of a plasticiser (e.g. water or glycerol). Three major phenomena occur: (1) fragmentation/disruption of the starch granular architecture; (2) cleavage of hydrogen bonds between starch macromolecular constituents; and (3) partial depolymerisation (also called 'dextrinisation') of amylose and amylopectin molecules.

Films may be cast or extruded from preparations of destructureated starch. The ratio of the two starch constituents (amylose and amylopectin) characterise materials with different properties. A preponderance of amylose (>70%) in starches gives stronger, more flexible films. The branched structure of amylopectin generally leads to films with poor mechanical properties (decreased tensile strength and elongation) [24].

Because these polymers in general have poor water resistance, and poorer mechanical properties than conventional polymers, they have been introduced into the market either as blends (with biodegradable aliphatic polyesters, such as Ecoflex from BASF, or Bionolle from Showa Polymers) or as grafts with others synthetic monomers such as vinylalcohol, caprolactone, or acrylonitrile [25, 26].

Another approach to improve starch polymers properties is the use of nanotechnology. BIOP Biopolymer Technologies is developing starch-polyester with clay nanocomposites. Materials obtained were proven to fulfil European directives on food contact materials and have suitable mechanical and barrier properties [27].

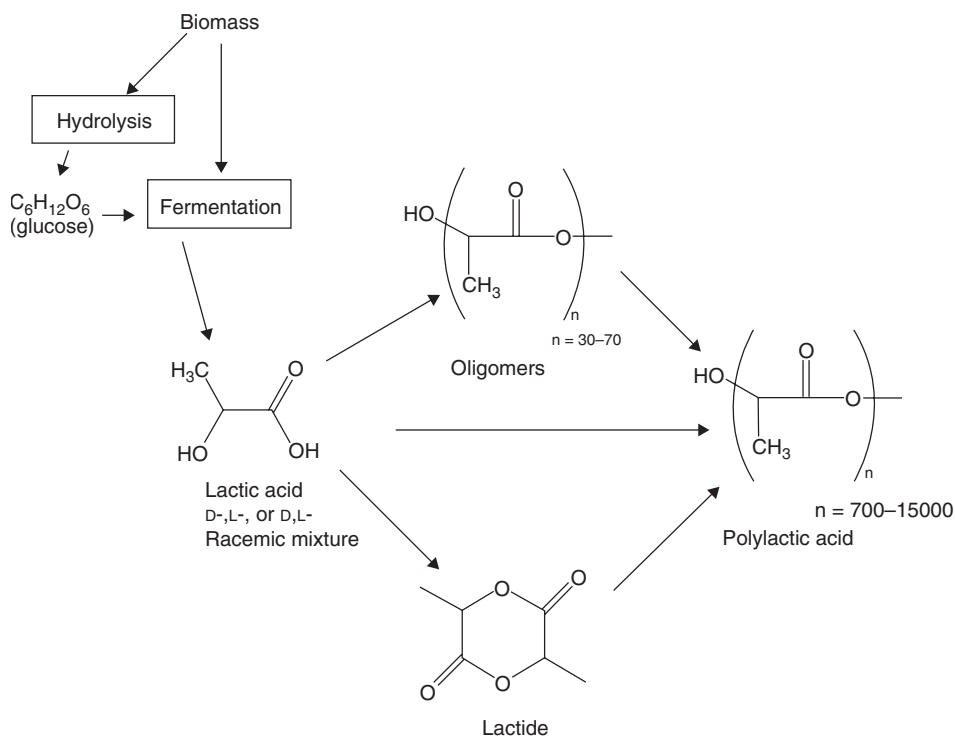
These starch polymers have found applications not only in food packaging, where they are used in the manufacture of trays, but also as windows for envelopes, carrier bags, disposal bags, and loose-fill packaging. Indeed, in the UK, 50% of all loose fill packaging is being manufactured from starch-based polymers and starch-based plastic foams formed by blending starch with PLA are used as loose-fill cushioning materials to protect against shock and vibration during transportation [28].

### 10.3.2.3 *Poly(lactic acid)*

Lactic acid is produced by the fermentation of carbohydrate material, usually glucose derived by hydrolysis from starch. The fermentation route can provide either enantiomer of lactic acid in high purity and dominates over chemical routes. The structure of lactic acid contains one asymmetric carbon, and can therefore exist as two stereoisomers. L-lactic acid is present naturally in numerous organisms, whilst the mirror image D-lactic acid is very rare in nature.

Two routes are currently used to obtain PLA, via polycondensation of lactic acid or via lactide (a dimer of lactic acid) ring opening (see Figure 10.8).

The direct synthesis of PLA by polycondensation features the typical drawbacks of step growth polymerisation [29]. High molecular weight polymers are obtained in relatively low yields [30], and these are very sensitive to the presence of impurities such as ethanol or acetic acid arising from the fermentation process. Nevertheless, high molecular weight PLA (300,000) can be attained by employing highly pure lactic acid and removing the water formed during the polycondensation [31], and another solution has been provided by the use of chain extenders to couple oligomers to provide high molecular weight products [32].



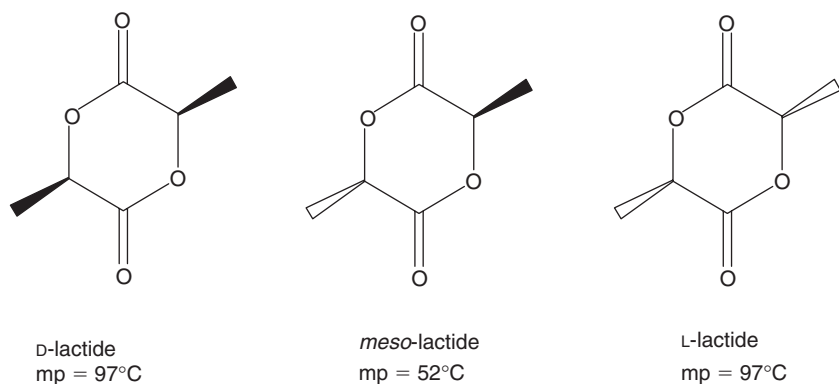
**Figure 10.8** Synthesis of PLA.

However, ring-opening polymerisation of the lactide, as practised by Cargill, appears more advantageous.<sup>2</sup> The latter is polymerised in the presence of tin/zirconium or titanium catalysts (this technique is also used to polymerise lactones, e.g. caprolactone on the large scale). Lactide, rather like lactic acid, but now possessing two asymmetric carbon atoms within its structure can exist as three stereoisomers: L-lactide, D-lactide, and the *meso*-lactide (see Figure 10.9).

Polymerisation of L-lactide affords a semicrystalline polymer with a melting point of 170–180°C and a glass transition temperature around 60°C. However, an amorphous material (no melting point and no glass transition temperature) is obtained from the polymerisation of the *meso* material. The mechanical properties of PLA (derived from L-lactide) are similar to those of PET (similar values of elasticity modulus, impact resistance, and rigidity), with a good retention of twist. In comparison with starch, barrier properties to gases are lower, but to humidity are higher. PLA has high surface energy and, therefore, can be easily printed.

The most useful property of PLA is the fact that the material is stable at room temperature and humidity, and will only biodegrade under active composting conditions [33].

<sup>2</sup> Mitsui has developed direct polymerisation to an industrial scale, but signed an agreement in 2001 to be supplied by Cargill-Dow for the Japanese market, according to a press release from Cargill in September 2001.



**Figure 10.9** The three lactide stereoisomers.

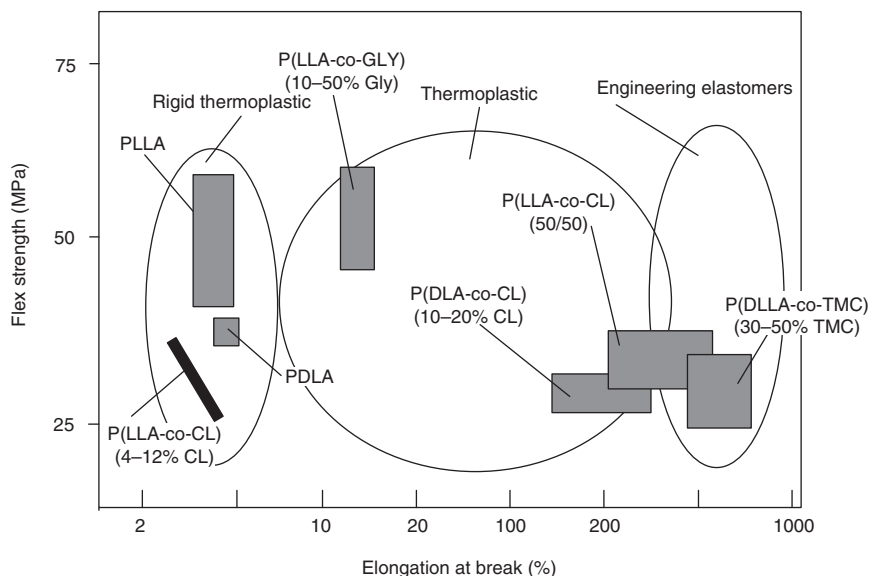
The properties of PLA can be modified by the use of copolymers and plasticisers. For example, the presence of a small amount of starch in PLA can improve the elongation of PLA film without affecting tensile strength. Figure 10.10, constructed using data provided by Hycail and from the literature [34], reveals the variation in strength and elongation for different PLA copolymers.

As shown, films prepared by copolymerisation with glycolic acid have increased elongation at break without any major change on the flexural strength, whilst those copolymerised with caprolactone or trimethylene carbonate show increased elongation but reduced strength [35].

In parallel, it has also been found that mechanical properties, flexural properties, heat distortion temperature, and oxygen gas permeability properties can be greatly improved by modifying PLA with organically modified layered silicate (OMLS) nanocomposites [36]. This is the basis of new PLA manufacture developed by Toyota.

As a packaging material, PLA film has been used to produce transparent films, trays, adhesives, and compostable tea bags (with PLA fibres) [37]. New technical improvements are likely to arise from the development of methods to improve stability during processing, blends and PLA-based composites, and new end-uses for the polymer in both packaging and non-packaging applications.

The price of PLA is predicted to equal that of PET by 2010 and therefore in the near future is expected to become a commodity polymer. It is being presently produced by Hycail, Galactic, Cargill (which is planning a production capacity of 0.5 million tonnes/year in 2010), and Toyota. PT Toyota Bio Indonesia was established in April 2001 to grow sweet potatoes for the manufacture of bioplastics. At present the global bioplastics market is just 20,000 tonnes annually, but Toyota calculates that as much as 30 million tonnes of the total annual plastics demand of 150 million tonnes could be replaced by bioplastics. In view of that potential, Toyota aims to increase production to 20 million tonnes with a potential sales value of five trillion Yen [38]. This would correspond to two-thirds of the global market of bioplastics by 2020, equivalent to 25% of Toyota's consolidated sales in 2003.



**Figure 10.10** Flex strength versus elongation at break for various PLA-copolymers. CL: caprolactone; TMC: trimethylcarbonate; GLY: glycolic acid.

### 10.3.2.4 Microbially synthesised polyhydroxy alkanoates

#### 10.3.2.4.1 Poly-3-hydroxybutyrate

Poly-3-hydroxybutyrate (PHB) is a biopolyester accumulated (similar to the function of starch or glycogen in other organisms) as a reserve of carbon and energy by a number of bacteria [39]. It is located in the cytoplasm in the form of granules of approximately  $0.5\ \mu\text{m}$  size. Under suitable conditions, up to 90% polymer can be accumulated with respect to bacteria dry mass. Isolation of the PHB requires breaking the cell walls by means of mechanical shear or enzymatic digestion followed by extraction of the polymer. This can be performed by means of washing in a centrifuge [40].

PHB was produced on the kilogram scale in the 1960s, but its stereo-chemical regularity led to progressive crystallisation with aging, thus making it brittle. This has been overcome by incorporation of co-monomers by grafting.

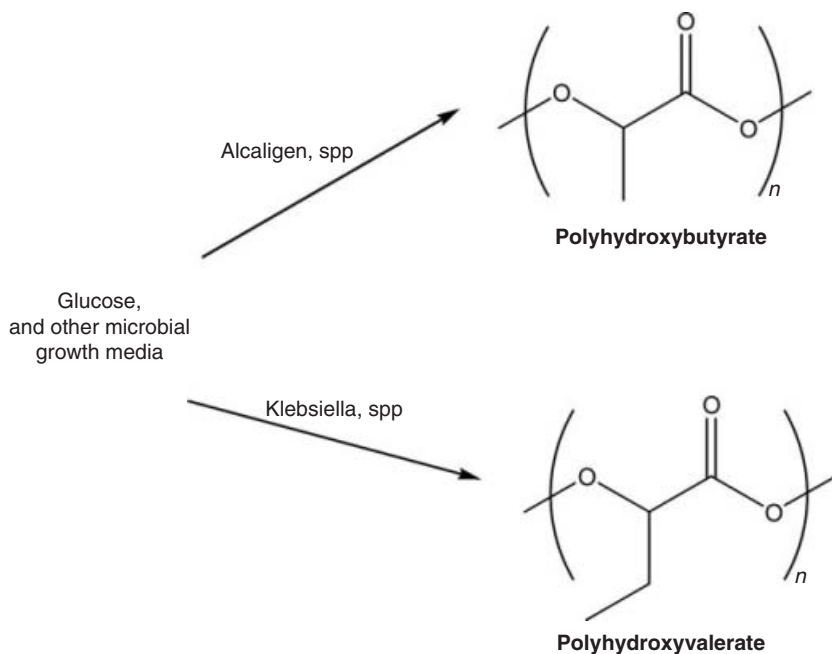
Biomer in Munich has been producing PHB with its own bacterial strains since 1994 [41]. Its current production amounts to several tonnes per year, with prices around £10/kg. At the present moment this polymer is much too expensive to be mass produced.

#### 10.3.2.4.2 Polyhydroxybutyrate-co-3-hydroxyvalerate

In the 1970s, PHBV (polyhydroxybutyrate-co-3-hydroxyvalerate) was successfully produced by using specific additives in the growth medium [42] (Figure 10.11).

Such an approach, whilst it improves the properties of PHB, is not cost effective, because the copolymer costs are higher, and its toxicity to the bacterium leads to lower production yields and also its presence affects PHB crystallisation kinetics, which results in longer





**Figure 10.11** PHB, PHBV chemical structures.

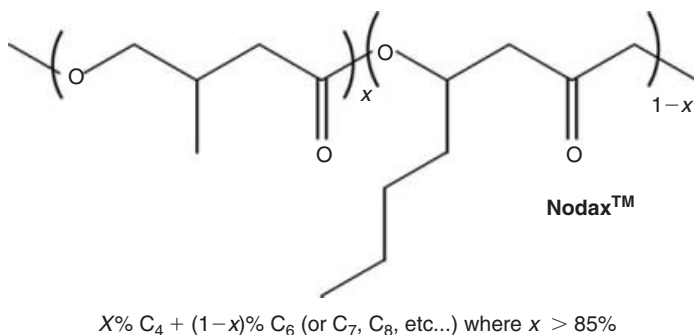
processing cycle times. Nevertheless, PHB could be toughened by the process of annealing by conditioning in an oven, a process that widens its application possibilities [43].

By comparison to PHB, which melts at 180°C, the melting point of PHBV can be lowered to 137°C by the introduction of 25% hydroxyvalerate [44]. This greatly improves thermoplastic processability [45]. In addition, mechanical stability is improved by an order of magnitude. Overall properties are comparable to polypropylene. Twenty years ago, as a result of the stabilisation of petroleum prices, the commercial interest in using PHB decreased. In the late 1980s, PHBV was commercialised by ICI under the trade name of Biopol. By 1996, the technology had been sold consecutively to Monsanto and to Metabolix, which is currently investigating direct synthesis of PHA in transgenic plants [46, 47].

#### 10.3.2.4.3 Polyhydroxybutyrate-co-hexanoate

Procter & Gamble and Kaneka have introduced a range of polyhydroxybutyrate-co-hexanoate (PHBH), under the trade mark of Nodax (Figure 10.12) [48]. The properties of Nodax are a function of the concentration of the hexanoate, which vary from hard with some flexibility (4%), hard elastic (6%), soft elastic (8%) to soft rubbery (18%), allowing to manufacture materials (injected moulded, films, or fibres), with similar mechanical properties to polyethylene/polypropylene using standard polymer technology.

A high surface energy (much like PET) means that these polymers can be dyed/printed without additional surface modification. Adhesion to LDPE and PP is good enough to avoid tie layers in multilayer structures. The oxygen barrier properties of Nodax approach those of EVOH. The potential use of Nodax as an additive to both PLA and thermoplastic



**Figure 10.12** Nodax polymers.

starch has been illustrated by the fact that Nodax improves a range of PLA properties (ductibility, high temperature hydrolytic stability, and heat sealability) and of starch processing characteristics (Nodax can lower starch melt temperature, improve starch UV and light stability, clarity) and in both cases improves barriers properties [49, 50].

Currently Procter & Gamble and Kaneka are working on new GM micro-organisms to increase production yields and decrease its price. The present Procter & Gamble/Kaneka cost target is £1.2/kg by 2007, with £0.4/kg in the long term (on a 50,000 tonnes/year basis, with new bacterial strains and new separation/purification techniques).

#### 10.3.2.5 Other aliphatic polyesters or polyesteramides

Polybutylene succinate (PBS) has a melting temperature of 114°C, and crystallises at about 75°C. Blown films have mechanical properties similar to LDPE films [51]. Incorporation of adipic acid in poly(butylene succinate-*co*-butylene-adipate) (PBSA) increases the degradation rate by lowering the crystallinity. PBS and PBSA are marketed by Showa Denko under the trade name Bionolle [52].

Polycaprolactone (PCL) is produced in the UK by Solvay, Dow Carbide in the US, and Daicel in Japan. It is obtained by a ring-opening polymerisation of the corresponding lactone. Its main application is in the formulation of polyurethane, but high molecular weight polymers are used in film manufacture. Its uses in drug formulation have been recently reviewed [53]. BioPlastics Inc, in the US is currently manufacturing bags with LDPE like mechanical properties by extrusion of PCL with destructured starches.

Polyglycolide (PG) is a polymer of glycolic acid, the simplest linear, aliphatic polyester. PG is obtained from the ring-opening polymerisation of glycolide, the dimer of glycolic acid. The resulting polymer has a glass transition temperature between 35–40°C. It is highly crystalline (around 45–55%) and is insoluble in water. Furthermore, PG does not dissolve in the majority of the most common organic solvents, the only exception being highly fluorinated solvents like hexafluoroisopropanol. PG is a biodegradable polymer that degrades through hydrolysis of its ester bonds. This material is used for the production of implantable medical devices and resorbable sutures [54]. The monomer is also used to modify other packaging polymers by reducing their water solubility.

Polyamides such as Nylon 6 are produced on a large scale, but only biodegrade very slowly. By contrast, polyesteramides with sufficient ester content, and a random distribution of amide moieties are biologically degradable. Copolymers of caprolactam (60%), adipic acid, and butanediol possess mechanical and melting characteristics similar to those of LDPE [55]. These were sold by Bayer from 1997 to 2001 under the trade name of BAK. A combination of high costs and unfavourable German legislation on biodegradable materials based on non-renewable resources was given as a reason for the abandonment of this business [56].

### 10.3.2.6 Chitin/chitosan

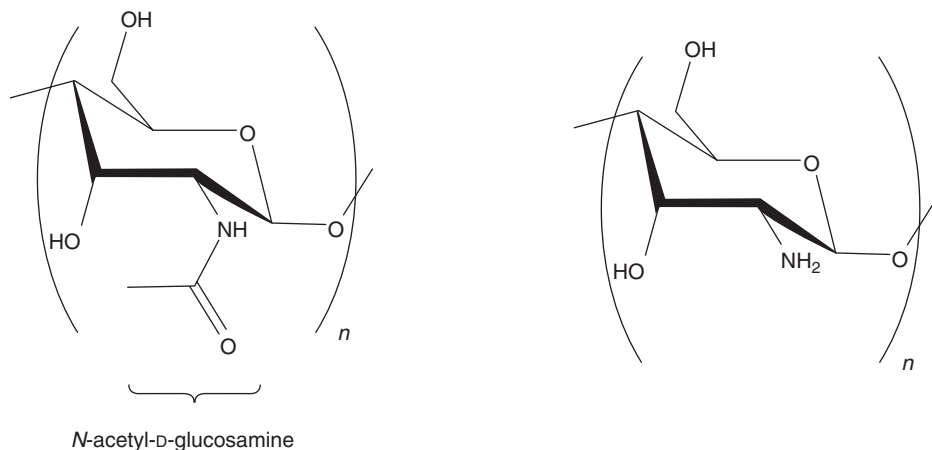
Chitin is the second most abundant polymer on earth after cellulose. The volumes of chitin production are much lower, due to its relatively high cost of extraction, and due to differences between batches caused by difficulties to prepare uniformly reproducible material in bulk quantities from various marine organisms [57].

Chitin is a polymer made of *N*-acetylglucosamine units joined to one another head-to-tail forming  $\beta$ -(1 $\rightarrow$ 4) linkages. It is the aminated equivalent of cellulose (Figure 10.13).

Chitin with a degree of deacetylation greater than 75% is known as chitosan [58]. The versatility of chitosan as an industrial material stems from the presence of a high proportion of free reactive amino groups. The processing of chitosan is a relatively unexplored field, compared to the more conventional materials, and the majority of applications are still at the development stage [59].

Chitosan films are clear, tough, and flexible with medium oxygen barrier properties [60]. Attempts to improve these by blending with PLA have failed, as the materials revealed were incompatible and phase separated [61]. Chitosan-based coatings can protect foods from fungal decay and modify the atmospheres of fresh fruits and vegetable.

Free-standing films have been prepared from chitosan and its derivatives, and their mechanical, barrier, and biodegradation characteristics are being evaluated in medical



**Figure 10.13** Chitin/chitosan structures.

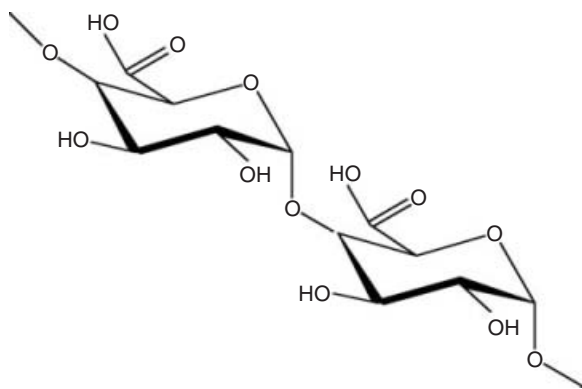
applications such as artificial skin and contact lenses [62]. Cross-linked chitosan films offer greater strength and resistance for handling. By being antifungal and antimicrobial, chitosan-based films and coating formulations have additional value. Chitosan-based composite coating formulations as well as films have been shown to prolong the shelf-life of banana, mango, and capsicum [63]. Application of chitosan induces the production of plant defence enzymes such as chitinase. A composite formulation called Nutri-Save, based on derivatised chitosan, is extensively used for shelf-life extension of apples, pears, pomegranates and so on.

#### 10.3.2.7 Pectin

Pectin is a complex anionic polysaccharide composed of  $\beta$ -(1 $\rightarrow$ 4) linked D-galacturonic acid residues (Figure 10.14), wherein the uronic acid carboxyls are either fully (HMP, high methoxy pectin) or partially (LMP, low methoxy pectin) methyl esterified. HMP forms excellent films. Plasticised blends of citrus pectin and high amylose starch give strong, flexible films, which are thermally stable up to 180°C. Pectin is also miscible with PVOH in all proportions. Potential commercial uses for such films are water soluble pouches for detergents and insecticides, flushable liners and bags, and medical-delivery systems and devices. These films are solution cast by air-drying at ambient temperature. Laminated films from pectin and chitosan together with either glycerol or lactic acid as a plasticiser have been prepared [64].

#### 10.3.2.8 Whey protein

Liquid whey, a by-product from cheese manufacturing, is produced in large quantities and its annual production is continuously rising. Even with a range of applications such as animal feed and clinical nutrition products, most of this whey has no end-use and creates serious waste disposal problems [65]. Liquid whey is the thin, watery proportion of milk that is obtained after coagulation of the curd (casein). Whey protein is then usually purified by membrane filtration to give whey protein concentrate (WPC, with 25–80% protein) or whey protein isolate (WPI, with >90% protein). WPI films provide excellent barriers against oxygen [66]. These films could function as controlled release carriers for antioxidants and antimicrobial agents, as well as supplementing the nutritional value of foods.



**Figure 10.14** Pectin structure.

#### 10.3.2.9 *Wheat gluten*

Gluten is the main storage protein in wheat. Wheat gluten is the cohesive and elastic mass that is leftover after starch is washed away from wheat flour dough. Commercially it is a by-product of wheat starch production via wet milling. Dry wheat flour comprises 9–13% protein and 75–80% starch. Commercial wheat gluten consists of wheat storage protein, with traces of starch and non-starch polysaccharides (10–14%), lipids (6–8%), and minerals (0.9–1.4%). The viscoelastic properties of wheat gluten once plasticised have been attributed to the existence of cystine amino acids which account for 2–3% of the total amino acid residues. During formation of dough, these residues undergo sulphhydryl–disulphide interchange reactions resulting in extensive polymerisation of gluten proteins, which create a strong viscoelastic and voluminous dough [67]. The low water solubility of gluten has been attributed to the low content of polar amino acids (14%), to numerous hydrophobic interactions between non-polar amino acids (40%), and to the presence of covalent disulfide bonds [68].

#### 10.3.2.10 *Soy protein*

Soy is a major traded commodity and soy protein-based polymers were used in the 1930s and 1940s for the production of fibres and plastics. The availability of cheap petrol and the biochemical inertness of petrochemical-based polymers eliminated these products from the market, and only recently has interest in this material re-emerged. The bulk of soy proteins are globulins, characterised by their easy solubility in salt solutions. Because soy plastics suffer from high moisture sensitivity and low strength, the main process used for the production of a soy protein-based polymer comprises the reduction of the disulfide bonds, and post-isolation acylation with carboxylic acid anhydride [69]. A material from soybean is presently produced by Dupont as Procoat, but it is only marketed as an adhesive substitute for casein. An alternative to this procedure involves modification via epoxysilane [70], or blending with stearic acid, using glycerol as a plasticiser [71]. Soy protein films formulated with protein bactericides (nicin and lysozyme) have been proposed for food packaging with enhanced antimicrobial properties [72]. Mechanical and barrier properties of soy protein films modified with calcium and glucono- $\delta$ -lactone have been reported to be better than the ones of soy protein isolate [73].

#### 10.3.2.11 *Rapeseed protein*

Rapeseed (*Brassica napus* L.) proteins are expected to be produced in large scale as co-products of biodiesel production in Europe. Their use in the manufacture of new polymers is currently being investigated in a European Union funded research project [74]. Separation of the proteins from glucosinolates and phospholipids has been developed on a pilot scale, and the most important proteins (cruciferin, napin, and lipid transfer proteins) have been purified [75]. The latest reports indicate that it was possible to produce films by casting of defatted proteinic rapeseed meal. However, the mechanical properties were weak, and the films were very hydrophilic. The chemical grafting of hydrophobic groups (via acylation) to the proteins led to an improvement of the film surface hydrophobicity, but not up to required specifications for commercial use. Films produced by casting with a protein

isolate by an aqueous enzymatic method afforded very low oxygen permeability rate of 85 cm/(m<sup>2</sup>h bar).

### 10.3.3 Conclusions

The current market for IWSP in packaging applications is quite small and is dominated by PVOH, EVOH, starch, and PLA. The market is likely to grow, because such polymers may provide materials with high technical specifications that have minimal impact on the environment. It has been shown that, in addition to the upgrading of the properties of current industrially important polymers, a full pipeline of new IWSPs is being developed to enter the market (Figure 10.15).

The synthetic IWSPs (PVOH, EVOH, EVA) and cellulose derivatives are in a mature stage of market development, while gluten, whey or rapeseed-based protein films are still at the proof of concept stage. A range of polymers based on renewable sources occupies the development pipeline in between. The rate of market growth in the IWSP sector is expected to be influenced by a range of factors:

- (1) *Social*: the sensitivity of the population to environmental concerns, which apparently is growing as consumers become willing to pay a premium price for biodegradable packaging [76].
- (2) *Legal*: a legislated reduction of greenhouse gas emissions, the Kyoto protocol, waste disposal and waste management regulations.
- (3) *Economic*: petroleum prices are expected to increase, before reaching the peak of reserve; the price of IWSPs is expected to decrease as a result of economies of scale, better sourcing of raw materials, and improved manufacturing technologies.
- (4) *Technological*: existence of important resources in R&D to increase the spectrum of potential substitutes for the family of five (PE, PP, PET, PVC, and PS) petroleum-based polymers.

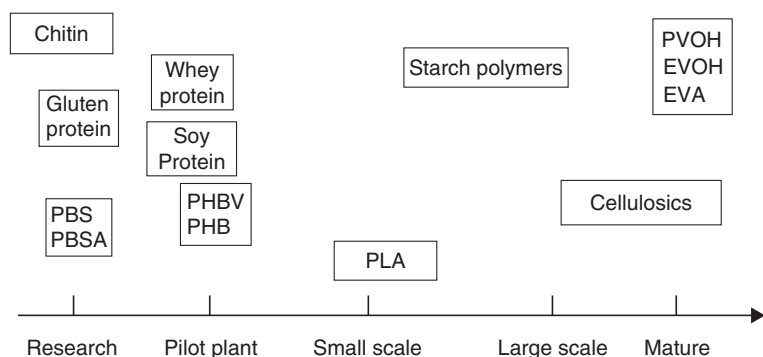


Figure 10.15 Pipeline of new IWSP.

## 10.4 Key characteristics of materials used in packaging

The main purpose of packaging is not only to protect the product from its surroundings, but also maintain the quality of the product for its shelf-life, while addressing communication, legal, and commercial demands.

Product quality when pertaining to food is a function of parameters such as the growth of pathogenic microbes, respiration, and maturation rates. The presence of gases, humidity, and light significantly affect these parameters, and are controlled by manipulation of the permeability of the materials used in packaging.

However in the choice of suitable materials, other factors must also be taken into account, such as thermo-mechanical properties (e.g. tensile strength, elongation, tear strength, puncture resistance and so on), migration/absorption, chemical resistance, and processability (thermoplasticity and sealability). The possibility to manipulate these parameters with either additives or new processing techniques makes the scenario even more challenging.

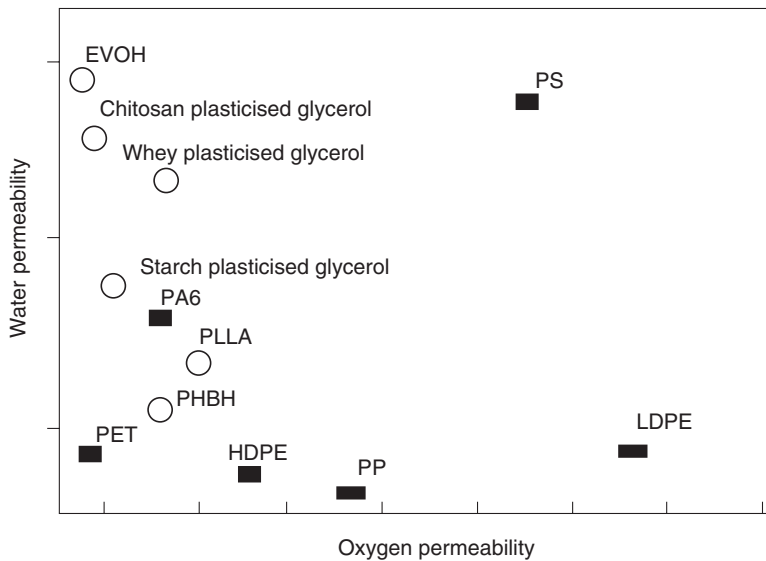
### 10.4.1 Barrier properties

A key characteristic of glass and metal packaging materials is their high barrier properties to gases and vapours. While polymers can provide an attractive balance of properties such as flexibility, toughness, lightweight, formability, and printability, they do allow the transport of gases and vapour to some extent. The selection of a barrier polymer for a particular application typically involves trade offs between permeation, mechanical and aesthetic properties as well as economic and recycling considerations [77]. Quality and shelf life are reduced when the packaged product, through interactions with the outside environment, gains or loses moisture or aroma, takes up oxygen (leading to oxidative degradation) or becomes contaminated with micro-organisms [78, 79].

The transfer of oxygen from the environment to packaged product has an important effect on quality and shelf life. Oxygen is essential when packaging fresh fruits and vegetables as they continue to respire after harvesting. The absence of oxygen can lead to anaerobic respiration in the package which accelerates senescence and spoilage. Oxygen also causes food deterioration such as lipid and vitamin oxidation, leading to major organoleptic and nutrient changes [80].

The modified atmosphere packaging of vegetables and fruits utilises not air ( $O_2$  21%;  $CO_2$  0.01%;  $N_2$  78%) but consists usually of a lowered level of oxygen (3–5%) for positive effect, and a heightened level of carbon dioxide, as  $CO_2$ -levels above 10–15% are needed to suppress fungal and bacterial growth significantly [81]. The balance is provided by  $N_2$ . This kind of packaging atmosphere slows down the normal respiration of the product and so prolongs the shelf-life of the product.

However, when packaging red meat (which does not respire, but the desirable, bright red colour of which, attributed to oxymyoglobin, is stabilised by the presence of  $O_2$ ), high  $O_2$  (60–80%) and  $CO_2$  (20–40%) levels are used and it has been found that they perform as effective bacterial and fungal growth inhibitors. A single oxygen impermeable layer of film may be used to seal the tray containing the meat. The elevated level of oxygen gas in the modified atmosphere maintains meat 'bloom' throughout distribution and display. Minimal time and handling in preparing the packages for merchandising is a notable advantage for high oxygen packaging. However, the use of such high concentration of oxygen may induce



**Figure 10.16** Oxygen/water permeability of IWSPs compared with conventional plastic packaging materials (Source: Ref. [82]).

undesirable off-flavours by oxidation of the meat. These erroneous flavours limit the acceptable shelf-life of the product even though the meat remains intrinsically safe.

Because of their hydrophilicity, IWSPs are excellent barriers to non-polar substances, such as lipids and some aroma compounds [83]. However, this characteristic makes their gas barrier properties very much dependent on the humidity conditions of the measurements, and may be the reason of variation of data presented in the literature.

Figure 10.16 presents oxygen and moisture vapour transmission rates (MVTR) on two dimensional axes. The oxygen permeability of IWSPs, compared to conventional mineral oil-based material is compared in Figure 10.16, showing that materials from both types overlap, and therefore suggesting that, upon the results of development made, new films based on the former could substitute the latter [84].

The oxygen permeability of both amylose and amylopectin rich starch films is reported to be as good as that from commercial EVOH at ambient humidity (relative humidity <15%), but above 20% such efficacy is lost [85]. Investigation of the gas permeability of potato starch films embedded with LDPE showed similar oxygen barrier characteristics to hydrophilic barriers, but with increasing water content this property was gradually lost [86].

The hydrophilic nature of IWSPs makes them unsuitable as moisture barriers for packaging applications unless certain modifications are applied.

Most natural-based polymers show a large water take up and high water permeability. They also change their mechanical and barrier properties in high moisture conditions, which is also a major disadvantage. This water sensitivity can develop a more spontaneous, non-controllable degradation under the influence of bacteria.



### **10.4.2 Thermal and mechanical properties**

The thermo-mechanical properties of packaging films are as important to the application as are the barrier properties. Adequate mechanical strength throughout the service life of a packaging application is necessary to ensure the integrity of a film. Thermal properties are important not only because of polymer processing technologies but also because of food preparation conditions (sterilisation steps), storage conditions (for freeze packed food), and cooking conditions (in the case of microwave packed food) [87]. Interactions between hydrocolloids, and small molecules, including water, plasticisers, lipids, and other additives dispersed in the space of the matrix contribute to the thermo-mechanical parameters of the films.

Quantitative information of the properties of the polymers is also essential for the packaging design process.

Among the many thermo-mechanical properties of plastic materials are tensile properties. Tensile testing provides data on yield strength, fracture strength (ultimate tensile strength), modulus of elasticity (Young's modulus), and elongation at break [88]. The maximum tensile strength is the maximum tensile stress that a film can sustain. Strain is the maximum change in the length of a test specimen before breaking. Elastic modulus is the fundamental measure of film stiffness [89]. Additives, and plasticisers in general, affect mechanical properties (as the content of plasticiser increases, tensile strength decreases, and elongation increases). In real life applications, the mechanical properties of water soluble polymers are sensitive to two other factors, temperature and humidity. Humidity behaves as a plasticiser, increasing elongation and decreasing strength, while as temperature increases, fracture strength (ultimate tensile strength), modulus of elasticity (Young's modulus), and elongation at break decrease.

### **10.4.3 Ageing of polymers**

The most common causes of ageing processes that films exhibit are (1) migration of additives from the matrix (common in the case of plasticisers, this leads to stiffer and less extendable materials, decreasing the protection function of the packaging); (2) chemical ageing (through oxidation).

### **10.4.4 Manipulation of critical barrier/thermo-mechanical properties**

The gas and vapour barrier and structural limitations outlined in the foregoing discussion have been addressed by the development of two general amelioration strategies: (1) 'pre-treatment' of the polymers, meaning a modification that is introduced into the polymer prior to a film being formed; or (2) 'post-treatment' meaning a modification that is introduced after the film is formed.

These treatments may be categorised as:

- (1) Modification of the plasticisers, which are key additives in the manufacture of films. In response to the problems caused by the use of glycerol, solutions have been to introduce substances with higher molecular weight, amphiphilic substances, including fatty acids. Antioxidants have been reported to improve oxygen barrier properties [90].
- (2) Chemical bonding of hydrophobic entities, or less soluble entities, cross-linking (mainly in protein films through reactive side groups in polypeptide chains), or cross-linking catalysed by enzymes (transglutaminase has been used in improving whey protein, and wheat films).
- (3) Gamma irradiation has been shown to improve both barrier and mechanical properties of films. A weaker form of electromagnetic radiation is UV radiation, which also has been used to improve starch and protein films [91, 92].
- (4) Thermal treatment of the solution under controlled conditions has been proved to improve properties of proteins films.
- (5) Blends with hydrophobic materials (lipids, waxes) have been shown to improve moisture resistance of both polysaccharide and protein films.
- (6) Development of multilayer films. The use of multilayer films is a standard procedure used by industry to ensure adequate film packaging properties for commercial needs. Therefore this is a technique to improve the moisture barrier properties of films derived from hydrophilic IWSP. A study on a biodegradable laminate film based on a naturally occurring carbohydrate polymer has been recently published [93].
- (7) Use of natural fibre composites. A large number of papers has been published on the advantage of using natural fibres as well as wood flour [94–96], which are to be light, renewable, and environmentally friendly. Research is focused in improving interfacial adhesion by surface treatment, chemical modification. More research is needed to develop practically viable methods to use these fibres. In spite of these difficulties, a large increase is expected in the use of such materials [97].
- (8) Intercalation of thermoplastic starch with clay nanocomposites has been shown to improve modulus strength, thermal resistance, and enhance hardness [98, 99], while the migration of additives has been shown to be at the level acceptable for food contact [100]. Elasticity of the films was however reduced though barrier properties are reported to be improved, without major change in the crystallinity of the polymers [101].

## 10.5 Conclusion

There has been a growing interest and effort over the last few years in the development of novel packaging concepts, which can play a proactive role regarding product preservation, shelf-life extension, and even improvement. Several strategies have been devised to exert a positive action over the packaged foodstuff, including antimicrobial agents used in food packaging (such as weak organic acids, enzymes, bacteriocins [102], triclosan, grape fruit seed extract, EDTA, essential oils, and fungicides), retention of desirable molecules (i.e. aldehydes, oxygen) and release of substances (i.e. carbon dioxide, aromas), and the use of oxygen scavengers. These new developments have been generally termed active packaging

technologies. However, many of these emerging active packaging technologies are finding in the versatility and special properties of plastic materials an efficient vehicle to exploit and enhance their commercial interest [103, 104].

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